Executables & Arrays

CSE 351 Autumn 2022

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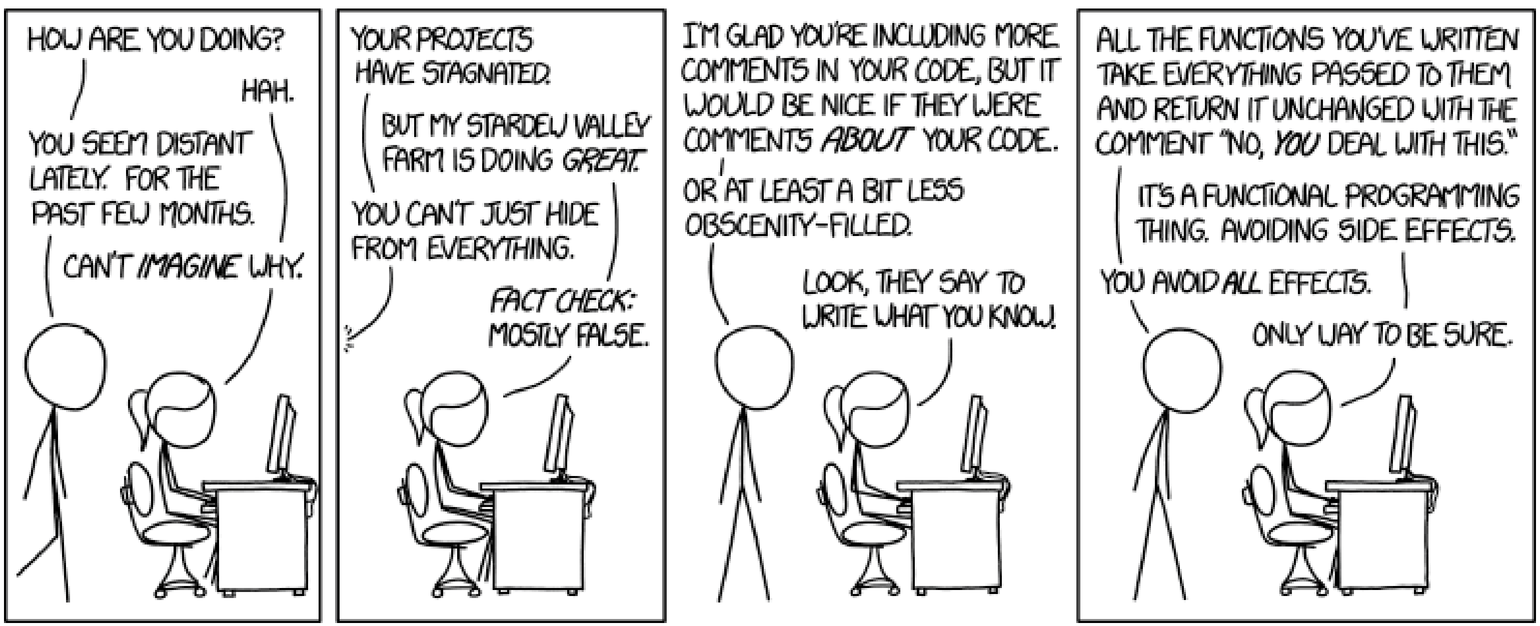

http://xkcd.com/1790/

Relevant Course Information

- Lab 2 & hw12 due Friday (10/28)
- hw13 due *next* Wednesday (11/2)
  - Based on the next two lectures, longer than normal

- Midterm (take home, 11/3-11/5)
  - Midterm review problems in section next week
  - Make notes and use the midterm reference sheet
  - Form study groups and look at past exams!

GDB Demo #2

- Let's examine the `pcount_r` stack frames on a real machine!
  - Using `pcount.c` from the course website

- You will need to use GDB to get through the Midterm
  - Useful debugger in this class and beyond!

- Pay attention to:
  - Checking the current stack frames (`backtrace`)
  - Getting stack frame information (`info frame <#>`)
  - Examining memory (`x`)

Instruction Set Philosophies, Revisited

- *Complex Instruction Set Computing* (CISC):
  Add more and more elaborate and specialized instructions as needed
  - **Design goals:** complete tasks in as few instructions as possible; minimize memory accesses for instructions
- *Reduced Instruction Set Computing* (RISC):
  Keep instruction set small and regular
  - **Design goals:** build fast hardware; instructions should complete in few clock cycles (ideally 1); minimize complexity and maximize performance
- How different are these two philosophies, really?

Instruction Set Philosophies, Revisited

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- How different are these two philosophies, really?
  - Both pursue **efficiency** (**minimalism** is a means to an end)

Mainstream ISAs, Revisited

Does anything feel “off” about this landscape?

x86

Designer	Intel, AMD
Bits	16-bit, 32-bit and 64-bit
Introduced	1978 (16-bit), 1985 (32-bit), 2003 (64-bit)
Design	CISC
Type	Register–memory
Encoding	Variable (1 to 15 bytes)
Branching	Condition code
Endianness	Little

Macbooks & PCs
(Core i3, i5, i7, M)
x86-64 Instruction Set

ARM

Designer	A[illegible]
Bits	32-bit, 64-bit
Introduced	1985
Design	RI[illegible]
Type	[illegible] Register
Encoding	AArch64/A64 and AArch32/A32 use 32-bit instructions, T32 (Thumb-2) [illegible]s mixed 16- and [illegible]
Branching	Condition code, compare and branch
Endianness	Bi (little as default)

Smartphone-like devices
(iPhone, iPad, Raspberry Pi)
ARM Instruction Set

RISC-V

Designer	University of California, Berkeley
Bits	32 · 64 · 128
Introduced	2010
Design	RISC
Type	Load–store
Encoding	Variable
Endianness	Little[1][3]

Mostly research
(some traction in embedded)
RISC-V Instruction Set

Tech Monopolization

- How many “dominant” ISAs are there?
  - 2: x86, ARM
- How many “dominant” phone brands are there?
  - 4: Samsung, Apple, Huawei, Xiaomi
- How many “dominant” operating systems are there?
  - 3/4: Android, iOS/macOS, Windows, Linux (?)
- How many “dominant” chip manufacturers are there?
  - 3: Intel, Samsung, TSMC

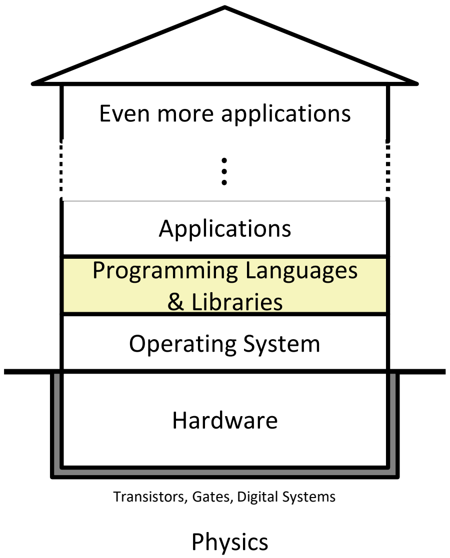
- It wasn’t always this way!
  - Combination of antitrust policies and (lack of) enforcement

Assembly Discussion Questions

- We taught you assembly using x86-64; you didn't have a choice
  - What are some of the advantages of this choice?
  - What are some of the drawbacks of this choice?
  - What are some possible assumptions we are making about our students or values we are forcing on our students with this choice?

The Hardware/Software Interface

- Topic Group 2: **Programs**
  - x86-64 Assembly, Procedures, Stacks, **Executables**



- How are programs created and executed on a CPU?
  - How does your source code become something that your computer understands?
  - How does the CPU organize and manipulate local data?

Reading Review

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

- Questions from the Reading?

Building an Executable with C (Review)

can compile multiple source files into a single executable

- 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`

text — C program (`p1.c p2.c`)

↓ **C**ompiler (`gcc -Og -S`)

text — Asm program (`p1.s p2.s`)

↓ **A**ssembler (`gcc -c` or `as`)

binary — Object program (`p1.o p2.o`) — Static libraries (`.a`)

↓ **L**inker (`gcc` or `ld`)

binary — Executable program (`p`)

↓ **L**oader (the OS)

Compiler (Review)

- **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 (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`

Producing Machine Language (Review)

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

- Addresses and labels are problematic because the final executable hasn't been constructed yet!
  - Conditional and unconditional jumps
  - Accessing static data (*e.g.*, global variable or jump table)
  - `call`

- 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

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

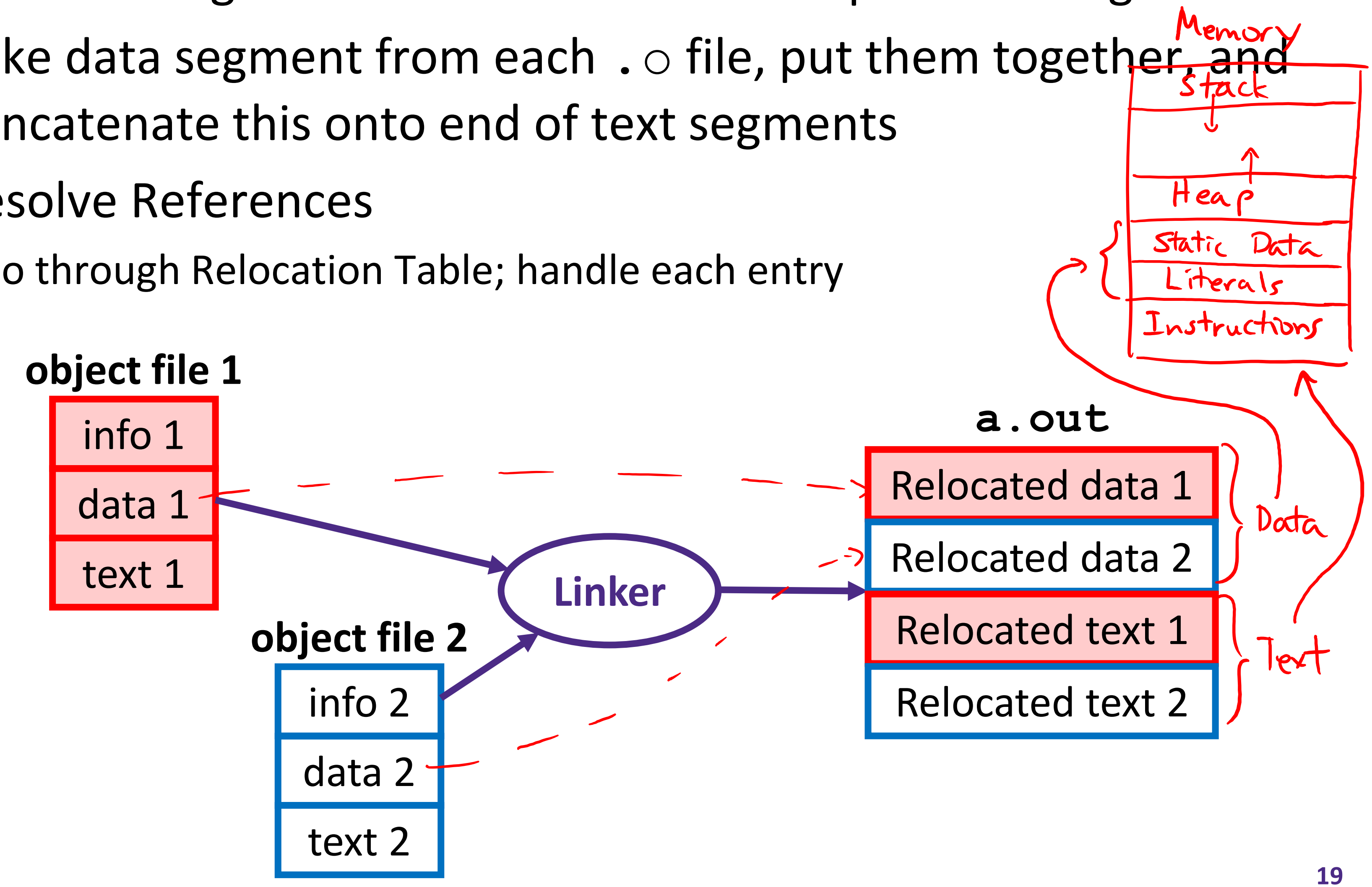
Linker (Review)

- **Input:** Object files (*e.g.*, ELF, COFF)
  - `foo.o`
- **Output:** executable binary program
  - `a.out` ← gcc's default executable name

- 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:

```
0000000000400536 <sumstore>:
                 36 37 38
  400536:        48 01 fe        add    %rdi,%rsi
                 39 3a 3b
  400539:        48 89 32        mov    %rsi,(%rdx)
                 3c
  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 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

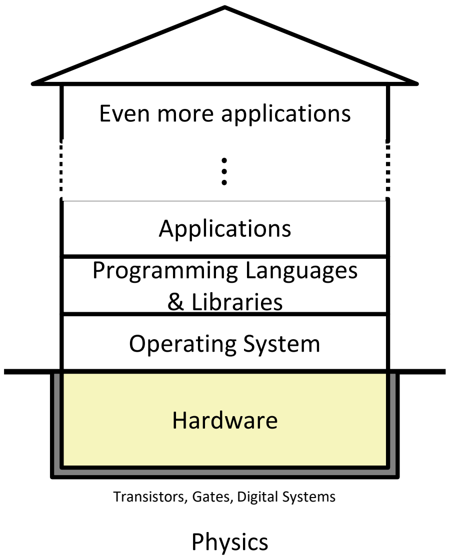
Loader (Review)

- **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

The Hardware/Software Interface

- Topic Group 1: **Data**
  - Memory, Data, Integers, Floating Point, **Arrays**, Structs



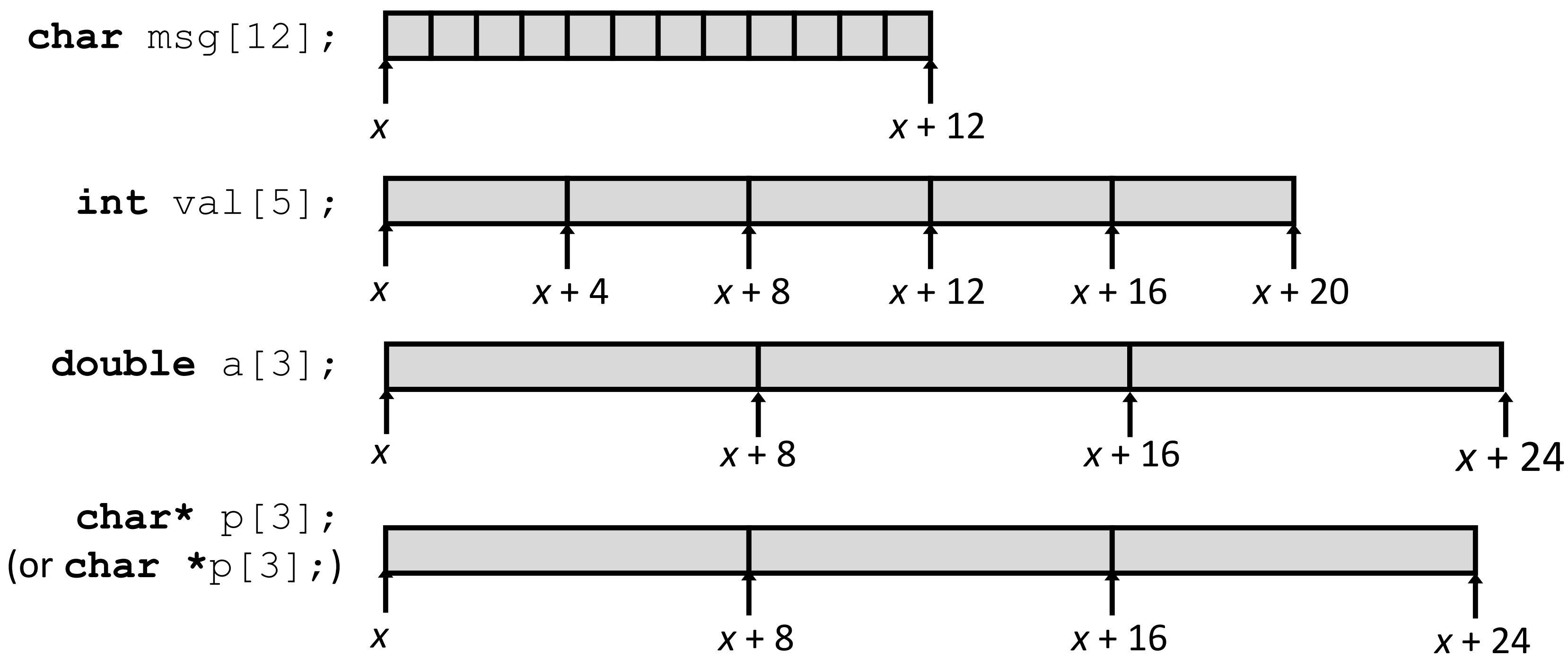
- How do we store information for other parts of the house of computing to access?
  - How do we represent data and what limitations exist?
  - What design decisions and priorities went into these encodings?

Data Structures in C

- **Arrays**
  - **One-dimensional**
  - Multidimensional (nested)
  - Multilevel
- Structs
  - Alignment
- ~~Unions~~

Array Allocation (Review)

- 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 (Review)

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

`int x[5];`

	3	7	1	9	5
index	0	1	2	3	4	"5"
a	a+4	a+8	a+12	a+16	a+20

- Reference Type Value

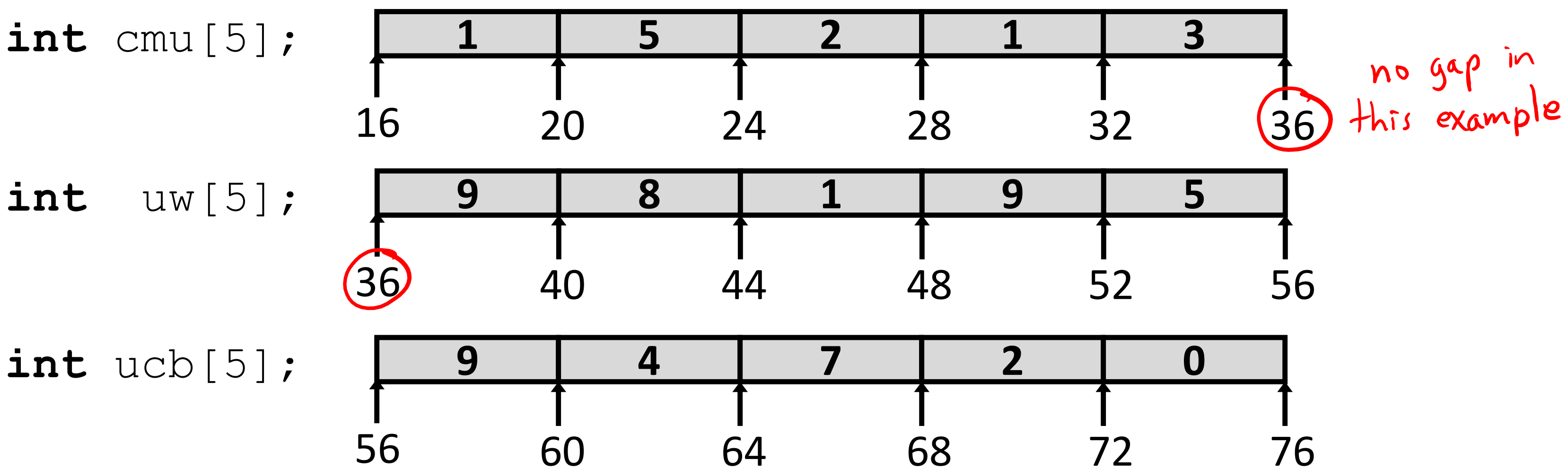
Reference	Type	Value
`x[4]`	**int**	5
`x`	**int***	a
`x+1` ← ptr arithmetic	**int***	a + 4
`&x[2]`	**int***	a + 8
`x[5]`	**int**	?? (whatever's in memory at addr `x+20`)
`*(x+1)`	**int**	7
`x+i`	**int***	a + 4*i

Array Example

brace-enclosed list initialization

```
// 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



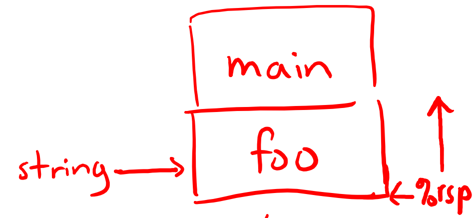
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

(could have allocated variables in-between)

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 (0^{th}) 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:

data will get overwritten by future stack frames

array is allocated on stack

```
char* foo() {
    char string[32]; ...;
    return string;
}
```

BAD!

returns stack addr that is < %rsp

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

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

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

Must explicitly pass the size!

Data Structures in C

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

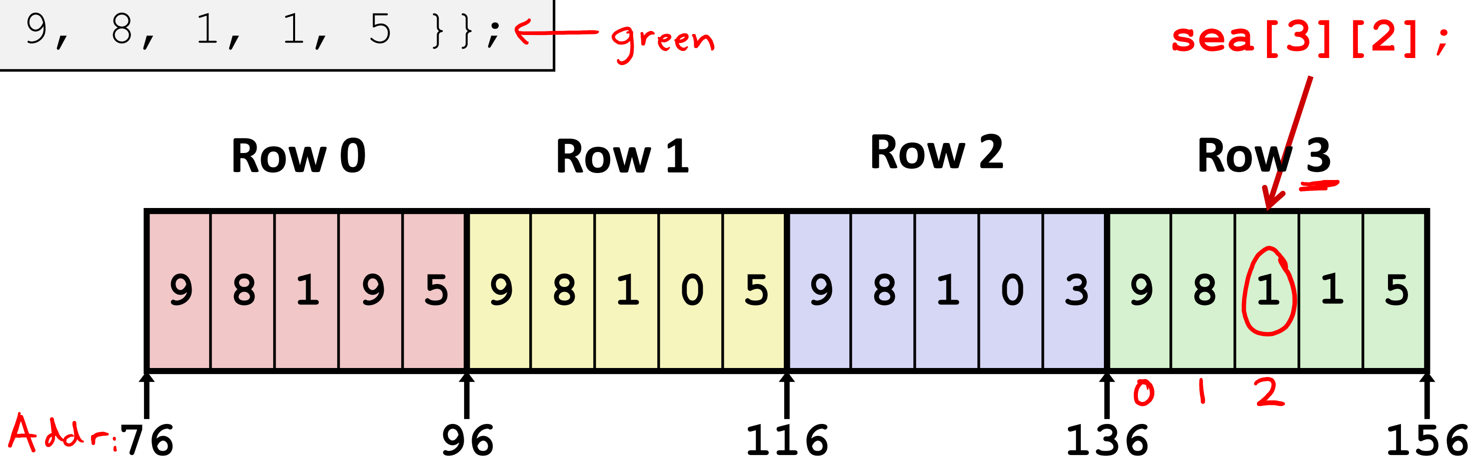
- What is the layout in memory?

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 }};
```

← red
← yellow
← blue
← green

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)

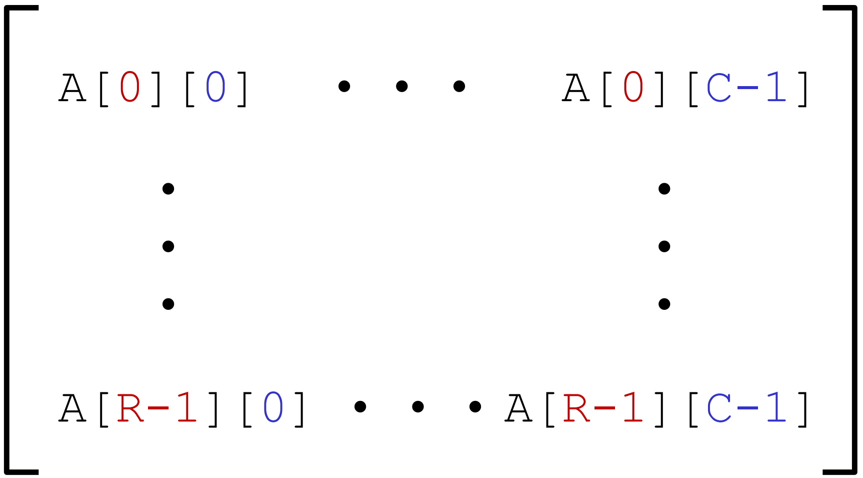
Two-Dimensional (Nested) Arrays

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

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

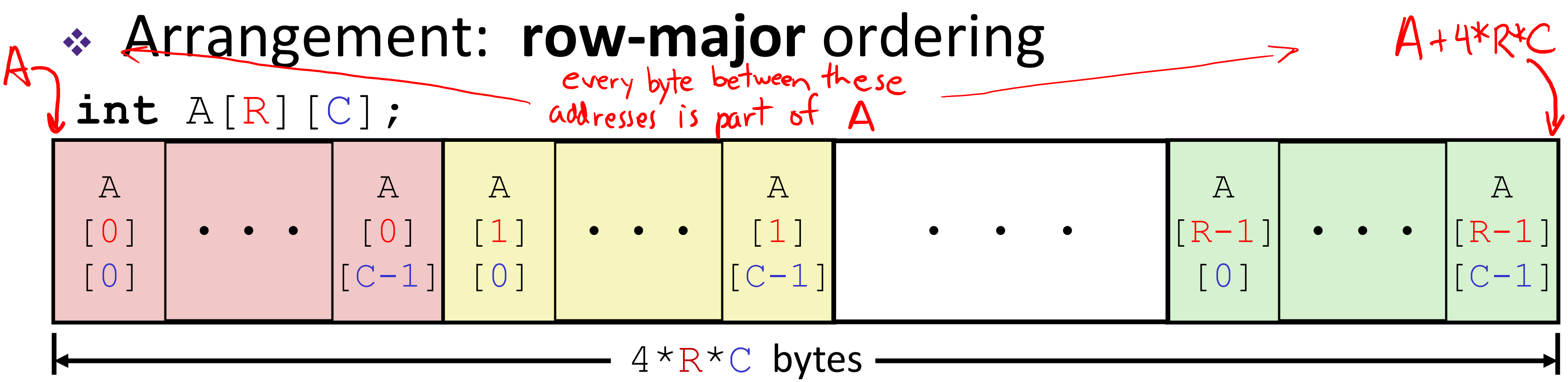
Two-Dimensional (Nested) Arrays

- 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

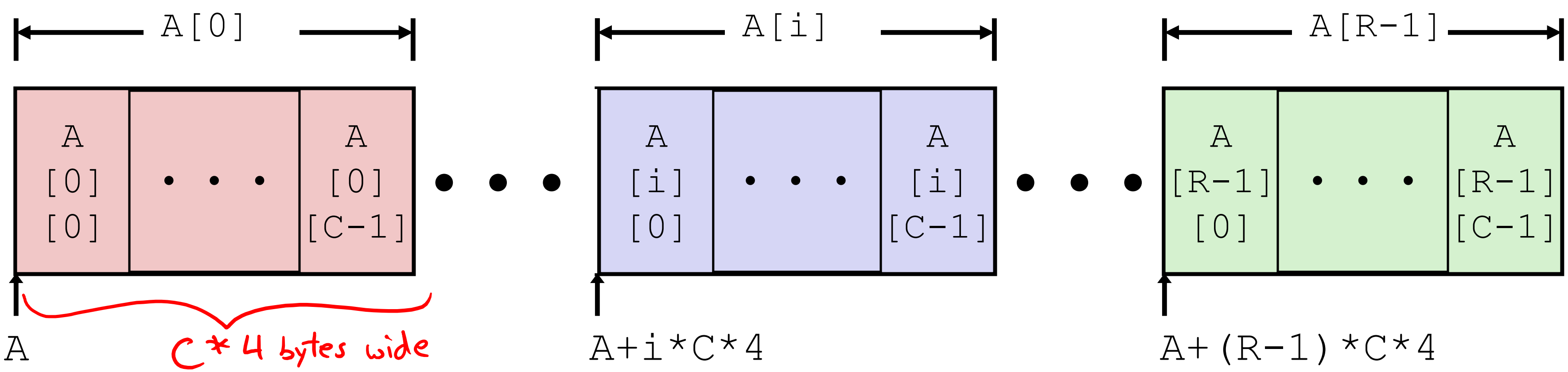
`int A[R][C];`



Nested Array Row Access

- Row vectors
  - Given **T** `A[R][C]`,
    - `A[i]` is an array of `C` elements ("row `i`") → just an address!
    - `A` is address of array
    - Starting address of row `i` `= A + i*(C * sizeof(`**T**`))`

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



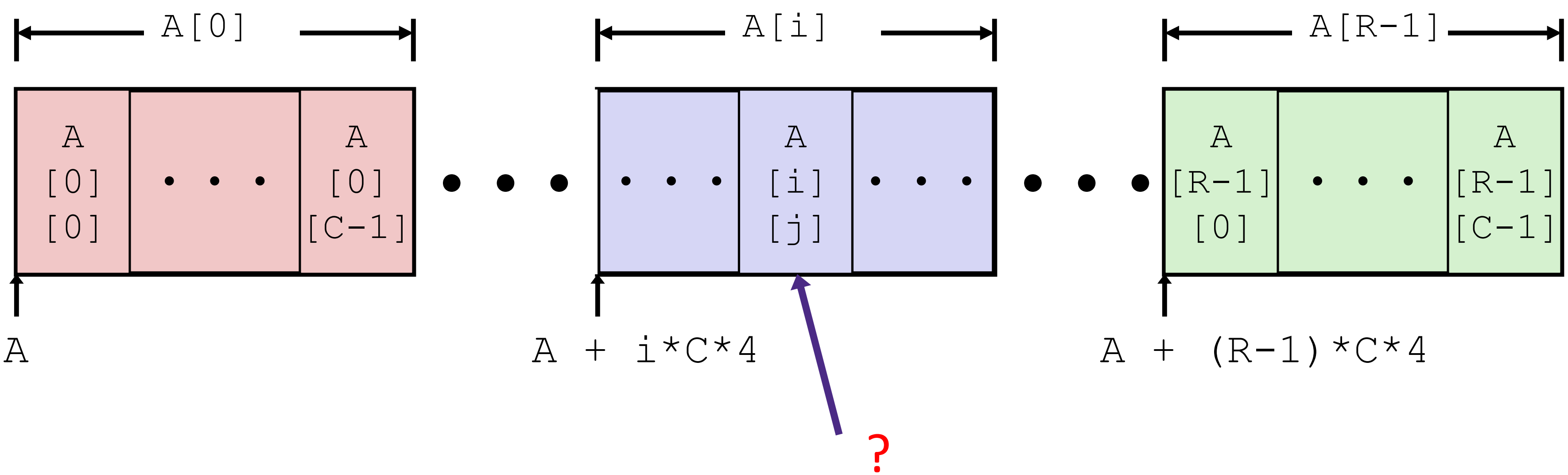
Nested Array Element Access

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

- Array Elements
  - `A[i][j]` is element of type **T**; let `sizeof(T)` = *t* bytes
  - Address of (`A[i]`)`[j]` is (A + i * C * sizeof(T)) + j * sizeof(T)

    address

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

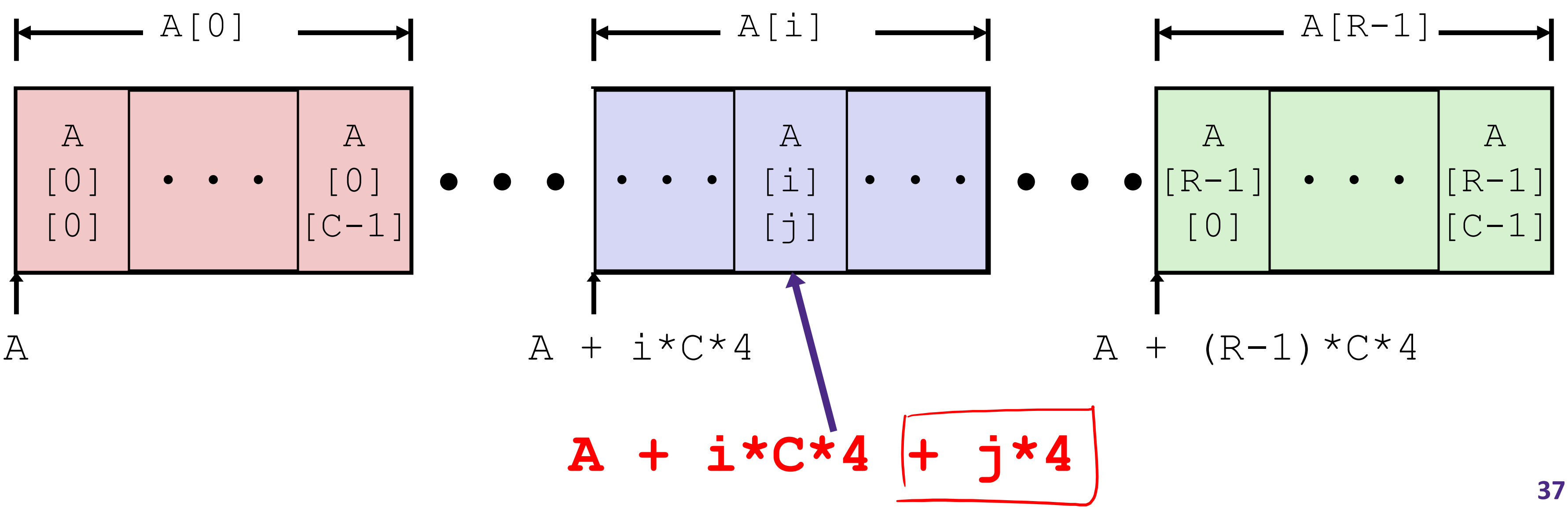


Nested Array Element Access

- Array Elements
  - `A[i][j]` is element of type **T**; let `sizeof(T)` = t bytes
  - Address of `A[i][j]` is

    `A + i*(C*t) + j*t = A + (i*C + j)*t`

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



Data Structures in C

- **Arrays**
  - One-dimensional
  - Multidimensional (nested)
  - **Multilevel**
- Structs
  - Alignment
- ~~Unions~~

Multilevel Array Example

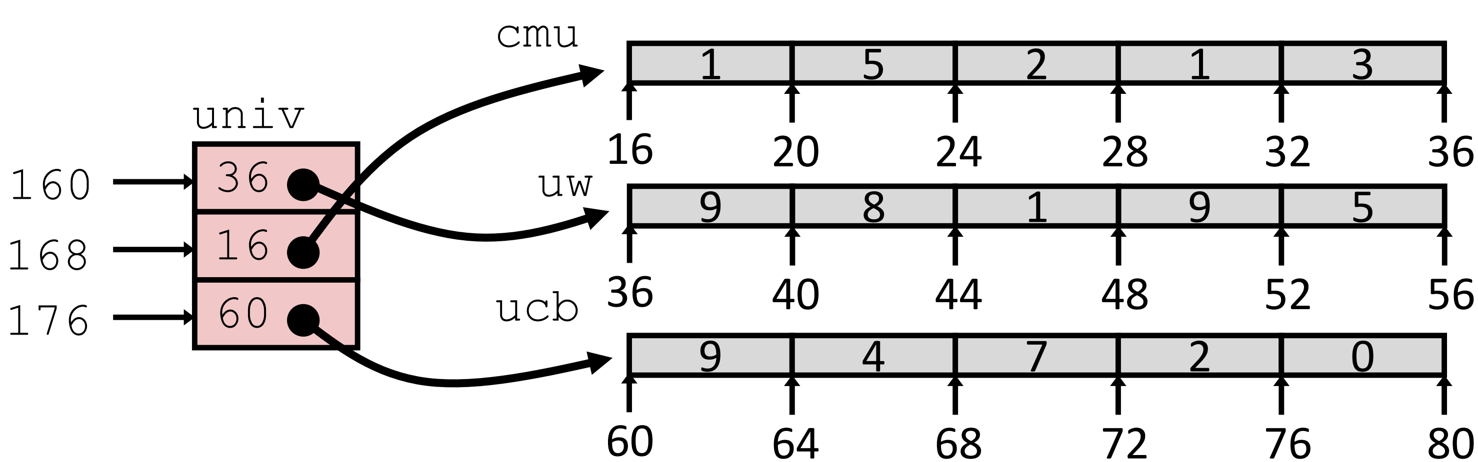
Note: this is how Java represents multidimensional arrays!

- Multilevel Array Declaration(s):

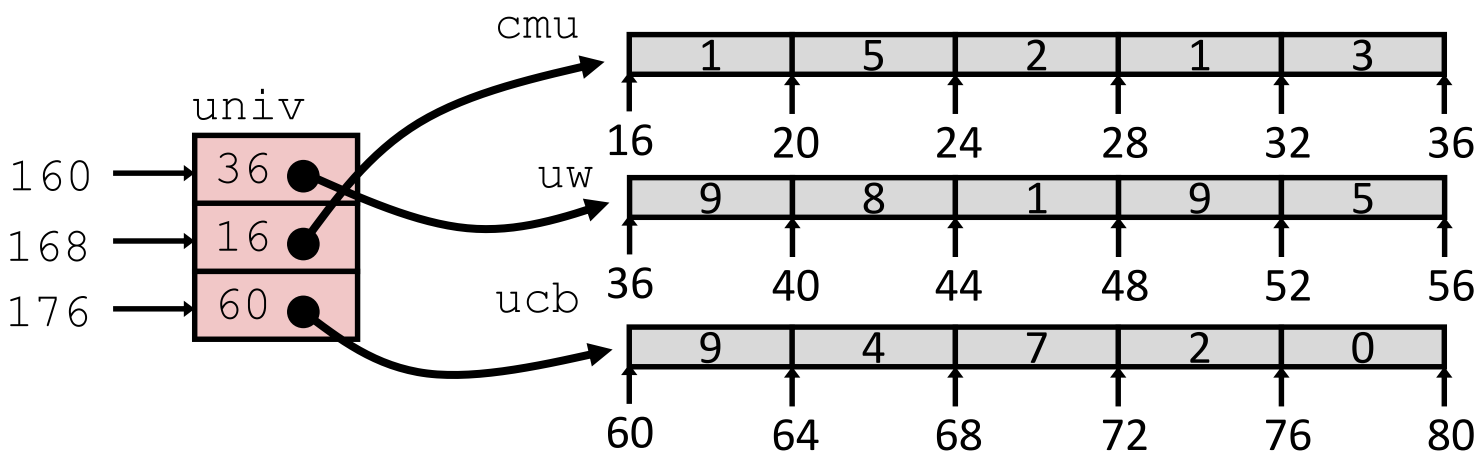
```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

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

  - Variable `univ` denotes array of 3 pointer elements
  - Each pointer points to a separate array of `int`s
    - *Could* have inner arrays of different lengths!



Multilevel Array Element Access



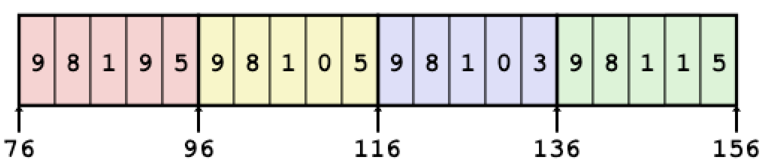

```
int get_univ_digit (int index, int digit) {
  return univ[index][digit];
}
```

- Mem[Mem[`univ+8*index`]+`4*digit`]
  - Must do **two memory reads**: (1) get pointer to row array, (2) access element within array

Array Element Accesses

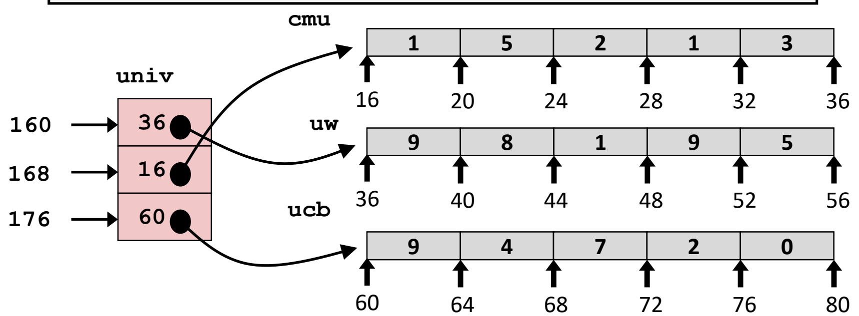
Multidimensional array:

```
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];
}
```



- Accesses *look* the same, but aren't:

Mem[sea+20*index+4*digit] Mem[Mem[univ+8*index]+4*digit]

- Memory layout is different:
  - One array declaration = one contiguous block of memory

Summary

- Building an executable
  - 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
- Arrays
  - Contiguous allocations of memory
  - No bounds checking (and no default initialization)
  - Can usually be treated like a pointer to first element
  - Multidimensional → array of arrays in one contiguous block
  - Multilevel → array of pointers to arrays
    - Each array/part separate in memory