Executables & Arrays

CSE 351 Spring 2024

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Playlist: [CSE 351 24Sp Lecture Tunes!]

Announcements, Reminders

- HW11 due tonight, HW12 due Wednesday, Lab 2 due Friday
- HW13/14 due next Wednesday (May 1st)
  - Based on the next few lectures, longer than normal.
- Mid-Quarter Assessment with Ken Yasuhara is next time!
- Midterm (take home, May 6th & May 7th)
  - Make notes and use the midterm reference sheet
  - Form study groups and look at past exams! ;)
  - Socio-technical content is fair game!
- GDB Demo for last class's final example code is now on Ed!

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

Mainstream ISAs, Revisited

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	Arm Holdings
Bits	32-bit, 64-bit
Introduced	1985
Design	RISC
Type	Register-Register
Encoding	AArch64/A64 and AArch32/A32 use 32-bit instructions, T32 (Thumb-2) uses mixed 16- and 32-bit instructions; ARMv7 user-space compatibility.[1]
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 (Wait, no Arm? They’re blueprints dealers! Computer architects with law degrees!)

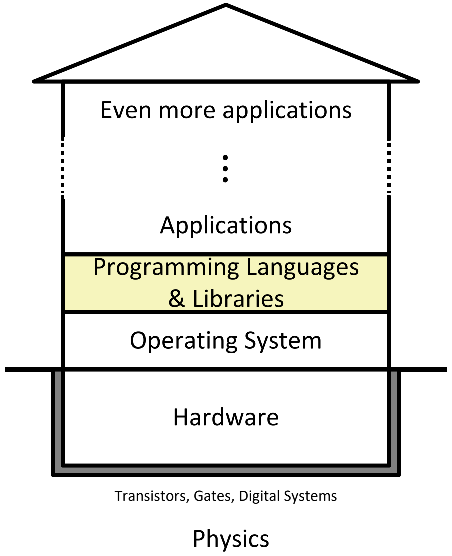
It wasn’t always this way!

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?

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

From LC 7: Architecture Sits at the Hardware Interface

Source code

Different applications or algorithms

Compiler

Perform optimizations, generate instructions

Architecture

Instruction set

Hardware

Different implementations

```
long mult2(long, long);

void multstore(long x, long y, long *dest) {
  long t = mult2(x, y);
  *dest = t;
}
```

GCC

```
multstore:
  pushq %rbx
  movq %rdx, %rbx
  call mult2
  movq %rax, (%rbx)
  popq %rbx
  ret
```

```
hex:
53
48 89 d3
e8 00 00 00 00
48 89 03
5b
c3
```

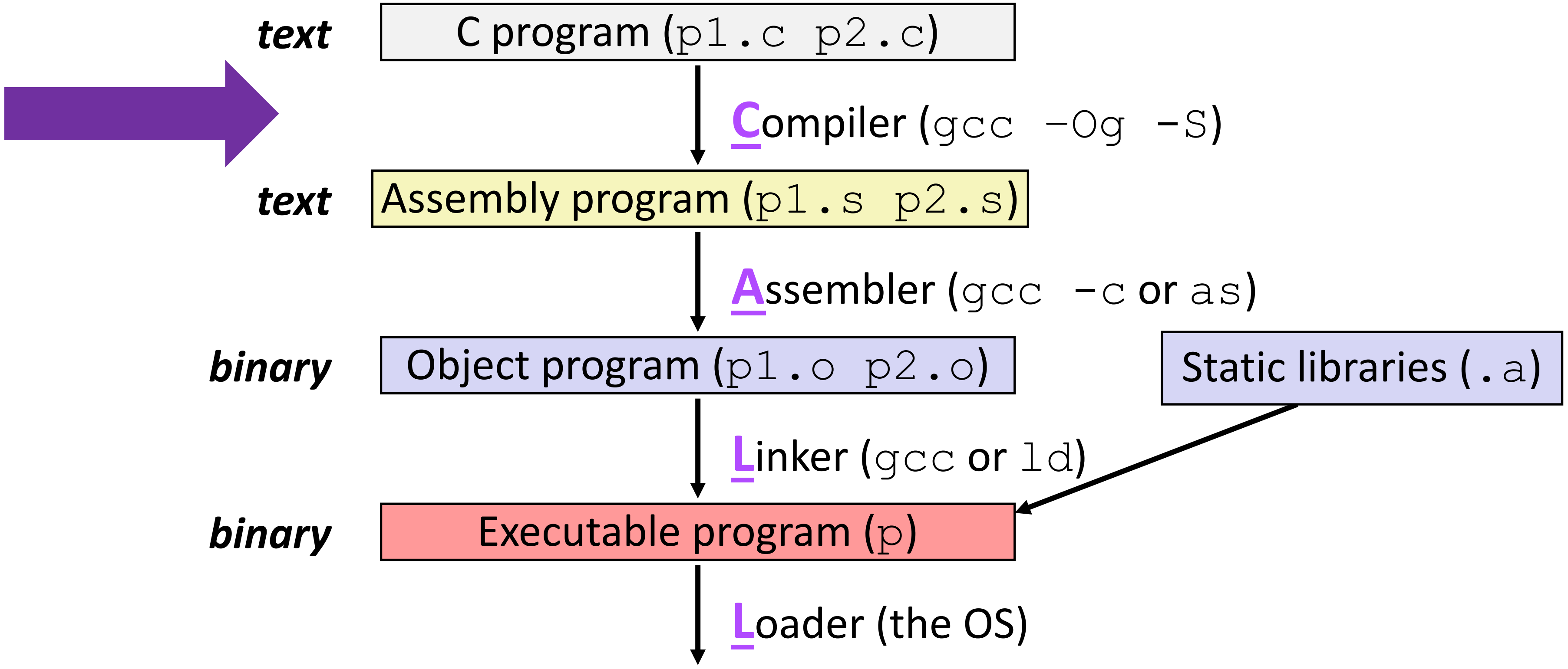
```
Binary:
0101 0011
0100 1000 1000 1001 1101 0011
1110 1000 0000 0000 0000 0000 0000 0000 0000 0000
0100 1000 1000 1001 0000 0011
0101 1011
1100 0011
```

See Section 3.2.2 in CSPP for more details…
I didn't lie, per se, but I didn't give all the details either.

CALL: Building an Executable with C (Review)

- Code in files `p1.c p2.c`
- Compile with command: `gcc -Og p1.c p2.c -o p`
- Run with command: `./p`

Put resulting machine code in executable file `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`
  - Example: `gcc -Og -S foo.c`

- 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! (CSE 401)
- 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)

Note: this is still "source code" in a sense – human-readable instructions, written out as text.

- 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

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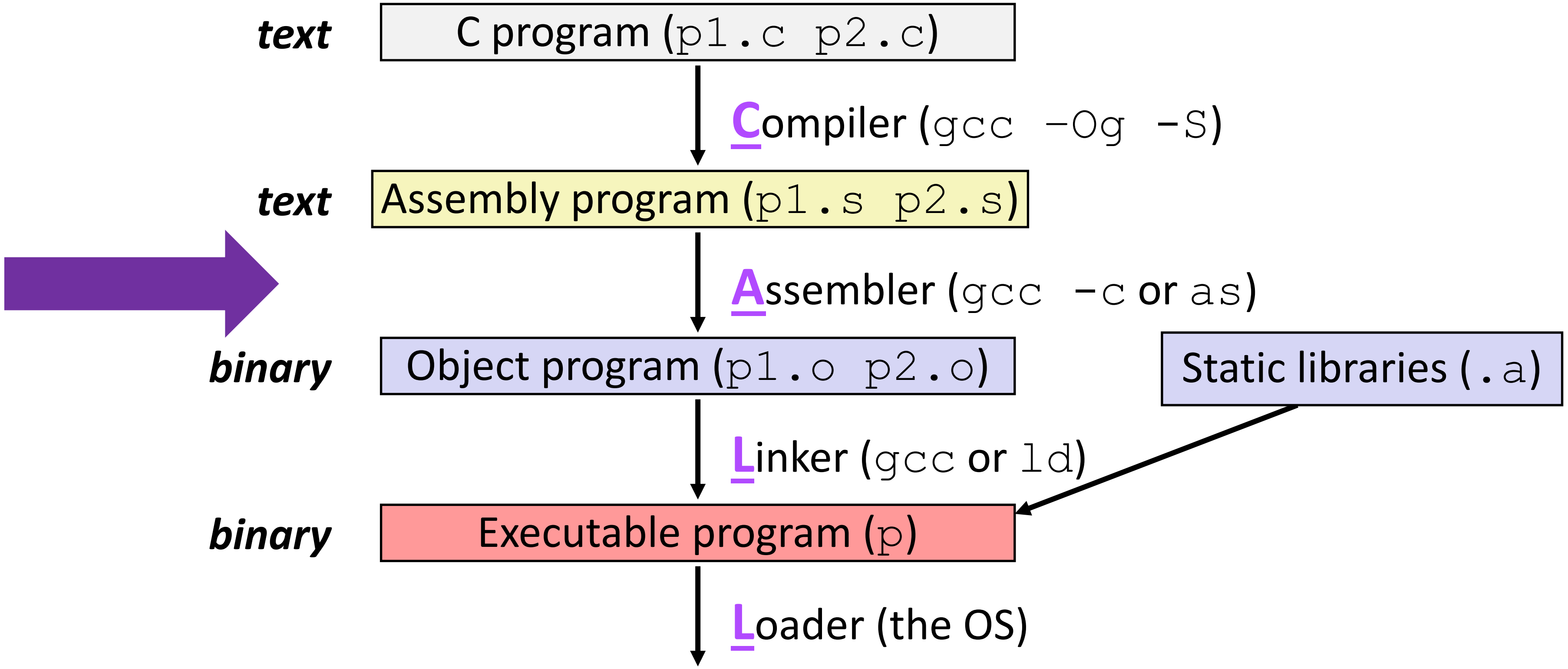

Assembler (Review)

- **Input:** Assembly language code (*e.g.*, x86, ARM, MIPS)
  - `foo.s`
- **Output:** Object files (*e.g.*, ELF, COFF)
  - `foo.o`
  - Very similar to assembly but a little different; Contains **object code** and **information tables**
- Example: `gcc -c foo.s`

- 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

Producing Machine Language (Review)

- **Simple cases:** arithmetic and logical operations, shifts, etc.
  - i.e. Instructions that don't reference addresses are totally complete by this step.
  - All necessary information is contained in the instruction itself!

- **Complex Cases:** Un/Conditional jumps, Accessing static data (*e.g.*, global variable or jump table), `call`
  - Addresses and labels are problematic because the final executable hasn't been constructed yet, and won't be until the next step (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
  i.e. "this is what I have & know about"
  - **Non-local labels** – function names usable 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)
  i.e. "what is still TODO"
  - 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
2) text segment: the machine code
3) data segment: data in the source file (binary)
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: `-g` flag creates debug information for use in GDB

- More info: ELF format
  - http://www.skyfree.org/linux/references/ELF_Format.pdf

CALL: Building an Executable with C (Review)

- Code in files **`p1.c p2.c`**
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Put resulting machine code in executable file **`p`**

text C program (`p1.c p2.c`)

Compiler (`gcc -Og -S`)

text Assembly program (`p1.s p2.s`)

Assembler (`gcc -c` or `as`)

binary Object program (`p1.o p2.o`)

Static libraries (`.a`)

Linker (`gcc` or `ld`)

binary Executable program (`p`)

Loader (the OS)

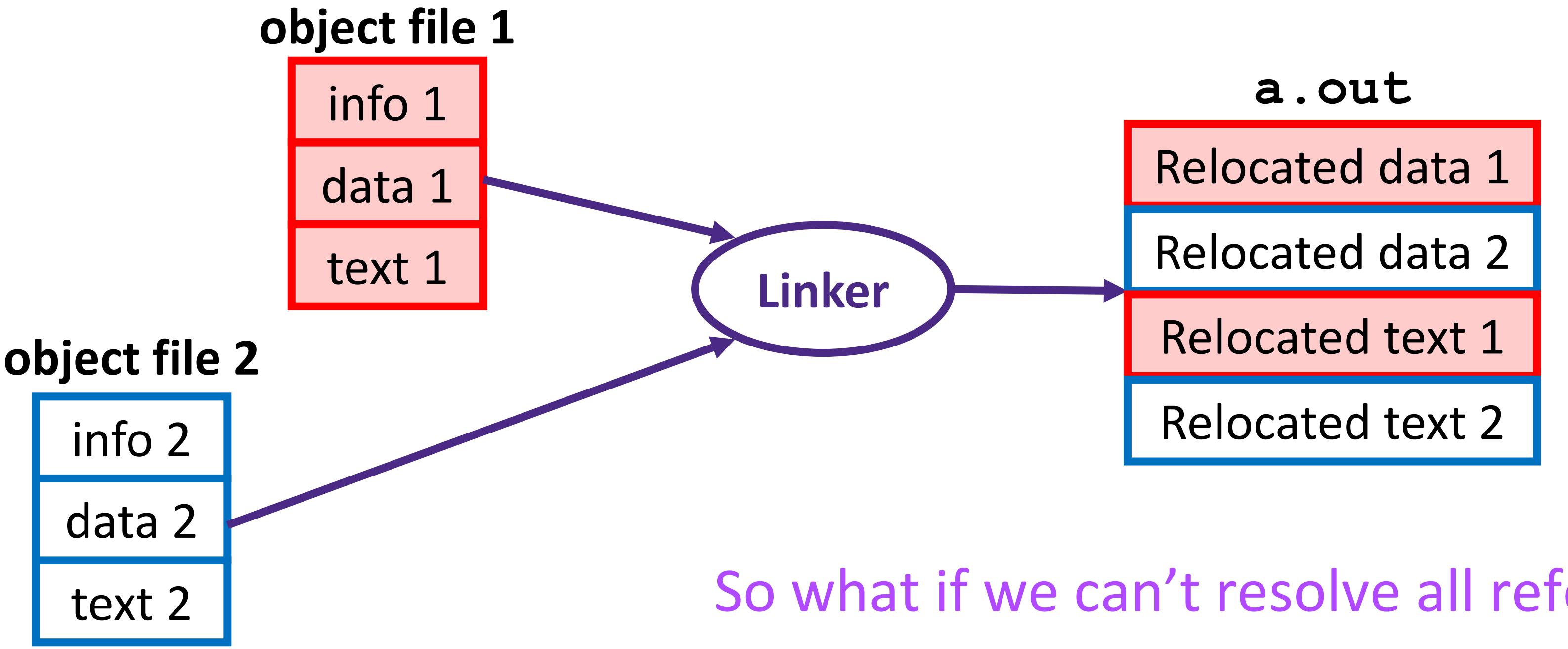
Linker (Review)

- **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 (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



So what if we can't resolve all references?

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

```
// tell the compiler that findme is in a different file
extern void findme();

int main() {
  findme();
  return 0;
}
```

```
$ gcc findme.c
/usr/bin/ld: /tmp/ccAQ36Zy.o: in function `main':
test.c:(.text+0xa): undefined reference to `findme'
collect2: error: ld returned 1 exit status
```

Disassembling Object Code (Review)

- Disassembled:

```
0000000000400536 <sumstore>:
  400536:  48 01 fe        add    %rdi,%rsi
  400539:  48 89 32        mov    %rsi,(%rdx)
  40053c:  c3              retq
```

- **Disassembler** (Ex: `objdump -d sum`)
  - Looks similar to assembly, but we actually have more info!
  - 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—you can (try to) disassemble anything…

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

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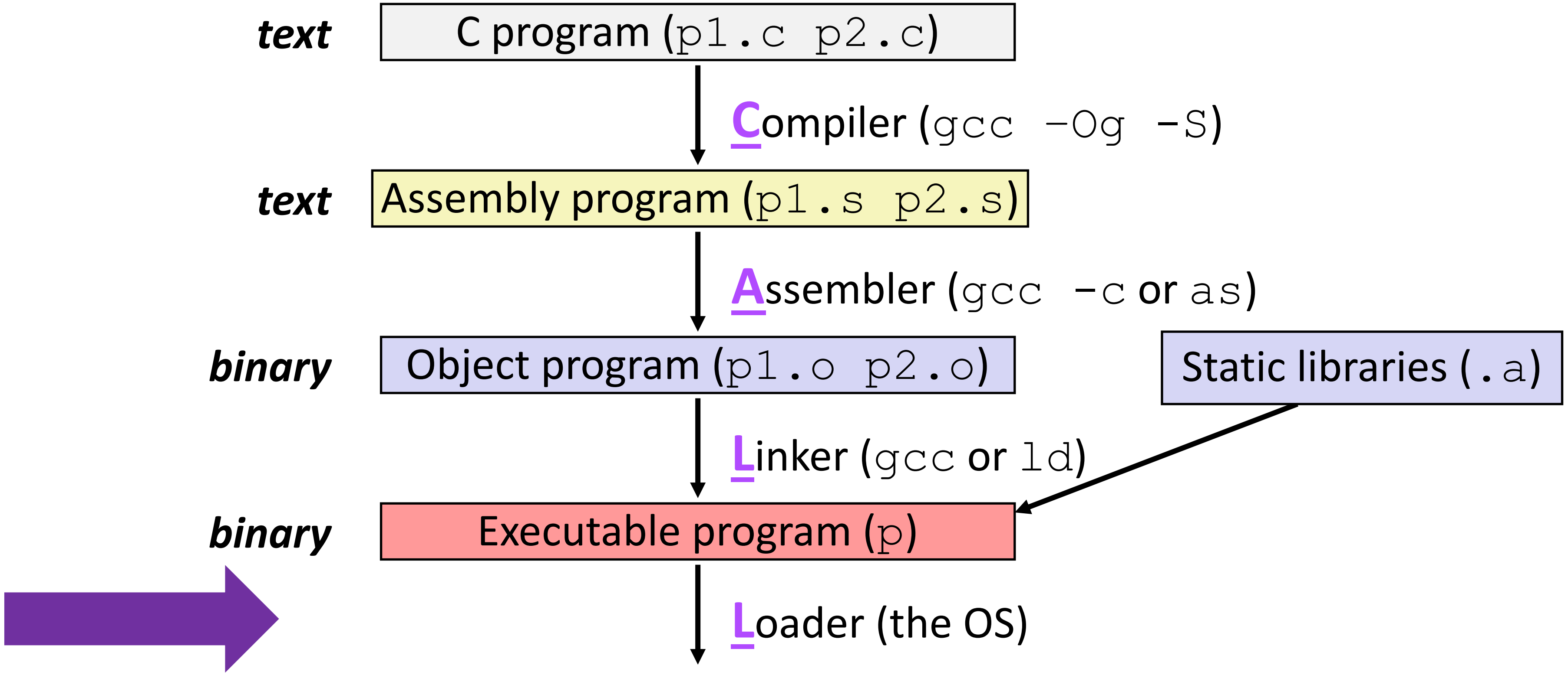


Loader (Review)

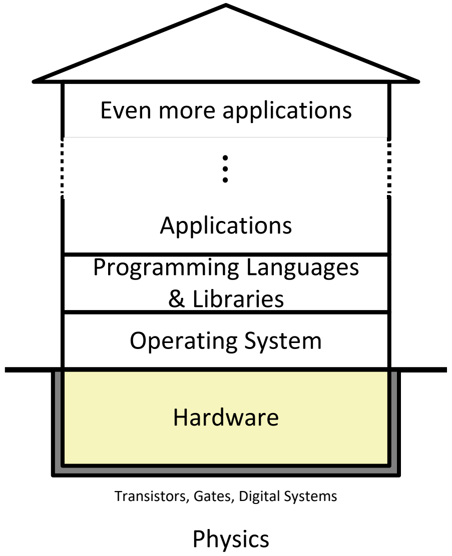
- **Input:** executable binary program, command-line arguments
  - `./a.out arg1 arg2`
- **Output:** <program is run>

- 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

- Want to implement this yourself? Take OS!

The Hardware/Software Interface

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



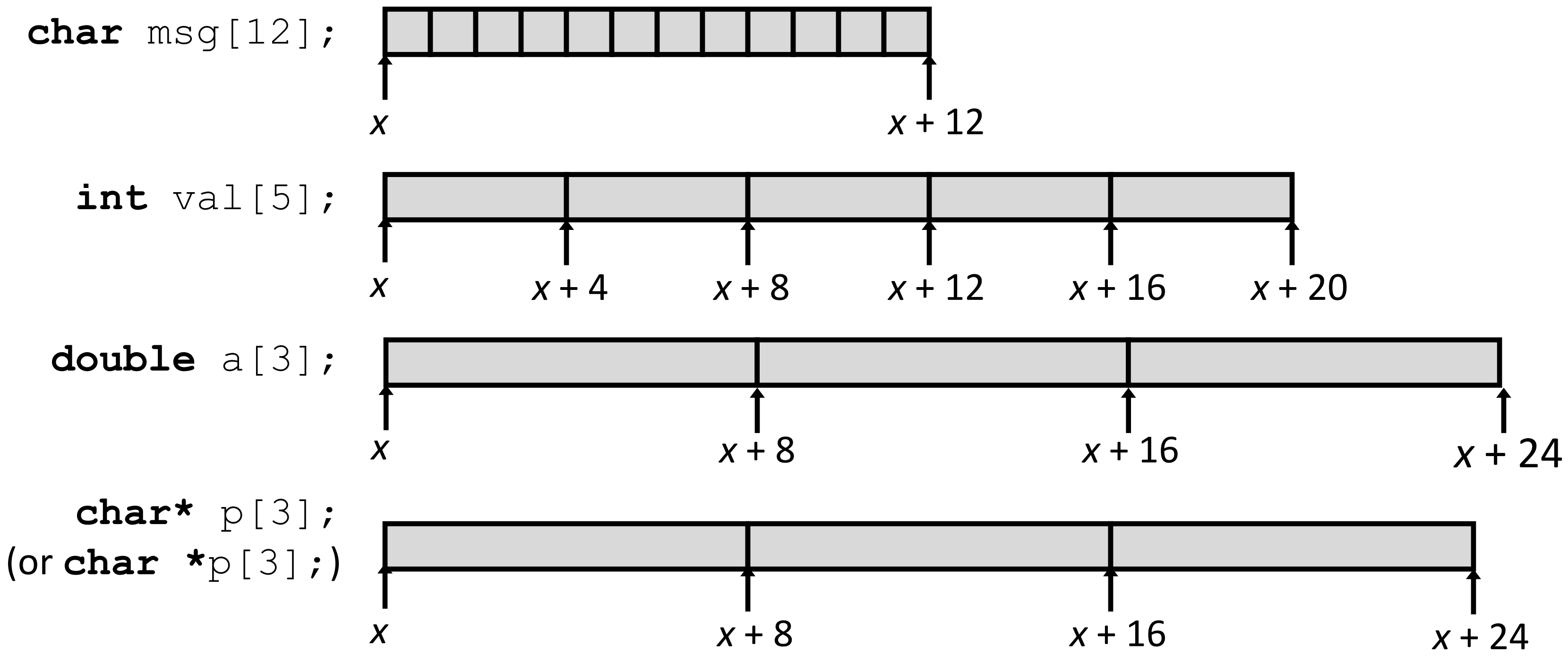
- How do we store information for other parts of the house of computing to access?
  - How do we represent data and what limitations exist?
  - What design decisions and priorities went into these encodings?

Data Structures in C

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

Array Allocation (Review)

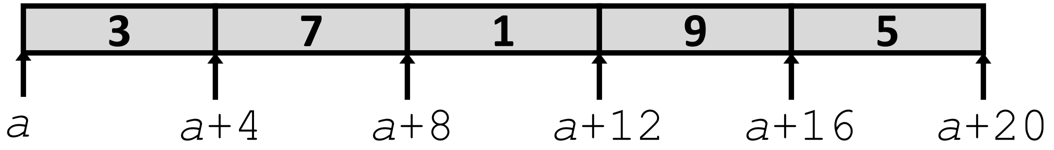
- Basic Principle
  - `T A[N];` → array of data type `T` and length `N`
  - Contiguously allocated region of `N*sizeof(T)` bytes
  - Identifier `A` returns address of array (type `T*`)



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];`

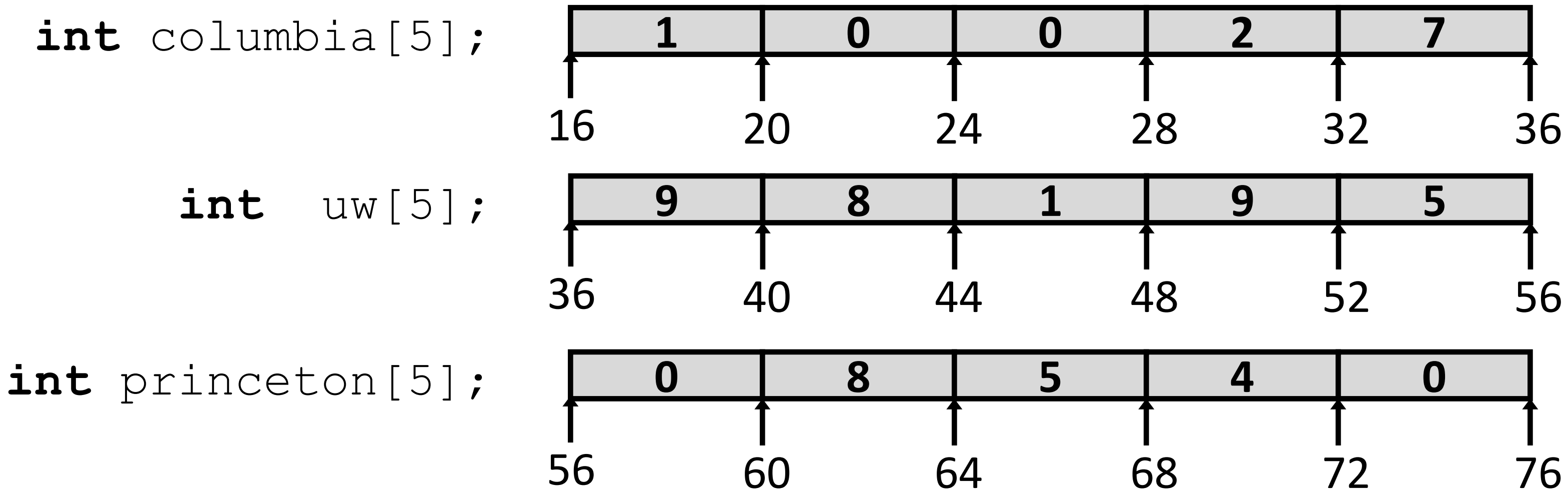


Reference	Type	Value
`x[4]`	**int**	5
`x`	**int***	a
`x+1`	**int***	a + 4
`&x[2]`	**int***	a + 8
`x[5]`	**int**	?? (whatever's in memory at addr `x+20`…)
`*(x+1)`	**int**	7
`x+i`	**int***	a + 4*i

Array Example

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

brace-enclosed list initialization; totally fine!



- 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 variable) & returns 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 allowed!—because it is a label
    - Cannot do : `ar = <anything>`

C Details: Arrays and Functions

- Declared arrays only allocated while the scope is valid:

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

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

Really `int* ar`—you just made `ar` into a pointer!

```
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

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 }};
```

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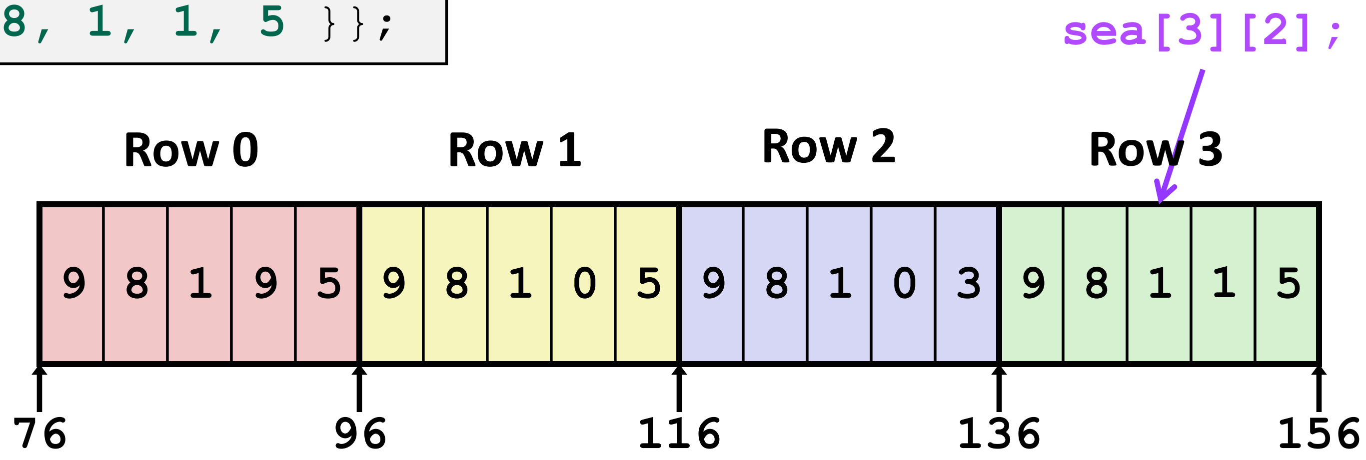
Remember, `T A[N]` is an array with elements of type `T`, with length `N`



- "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

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

`int A[R][C];`

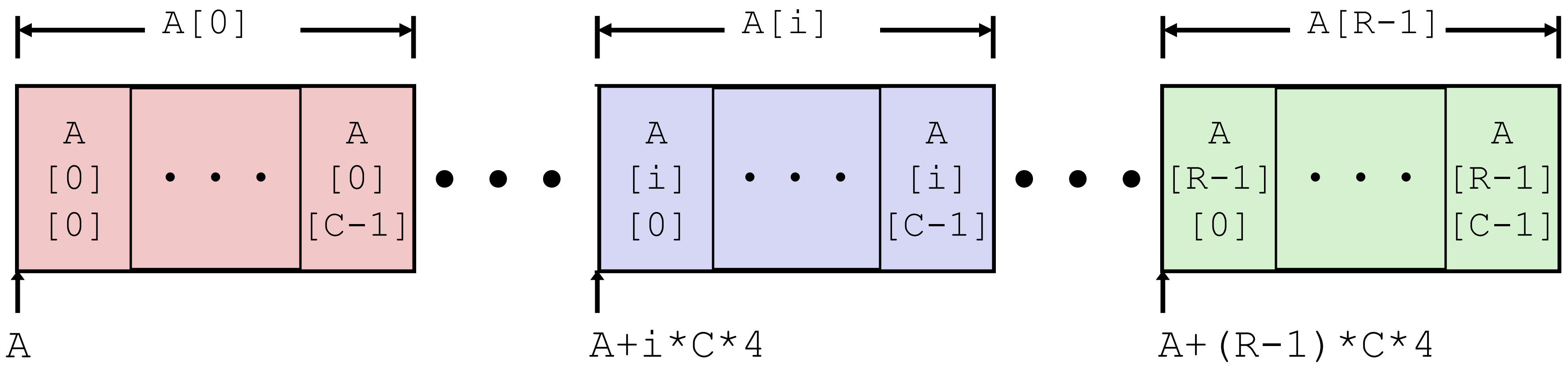
A[0][0]	• • •	A[0][C-1]	A[1][0]	• • •	A[1][C-1]	• • •	A[R-1][0]	• • •	A[R-1][C-1]

4*R*C bytes

Nested Array Row Access

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

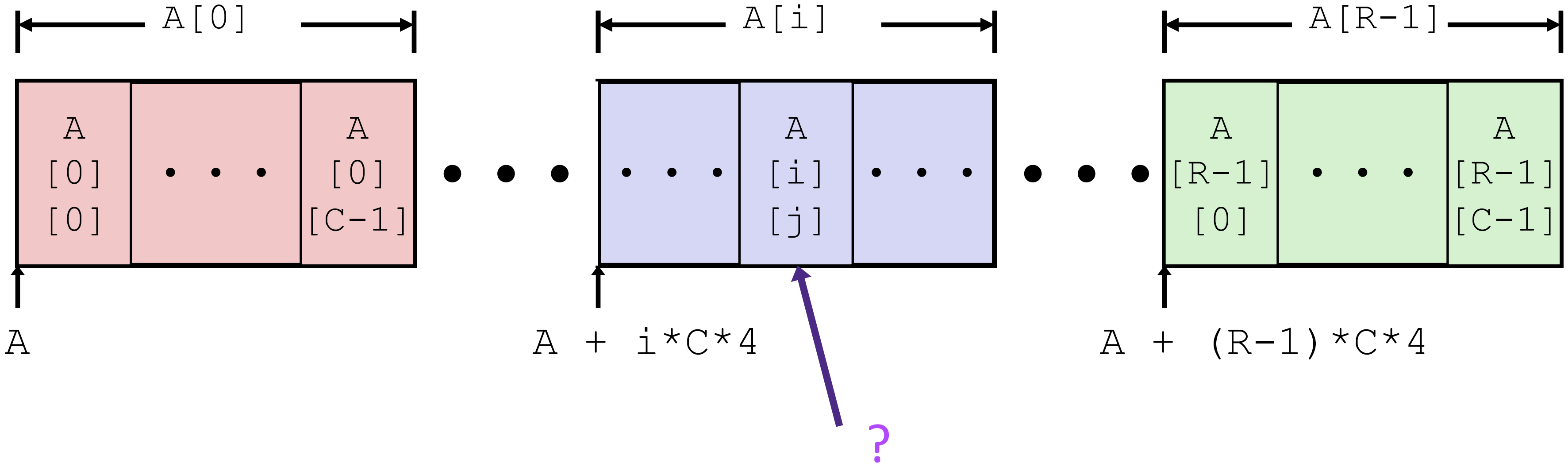
`int A[R][C];`



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

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

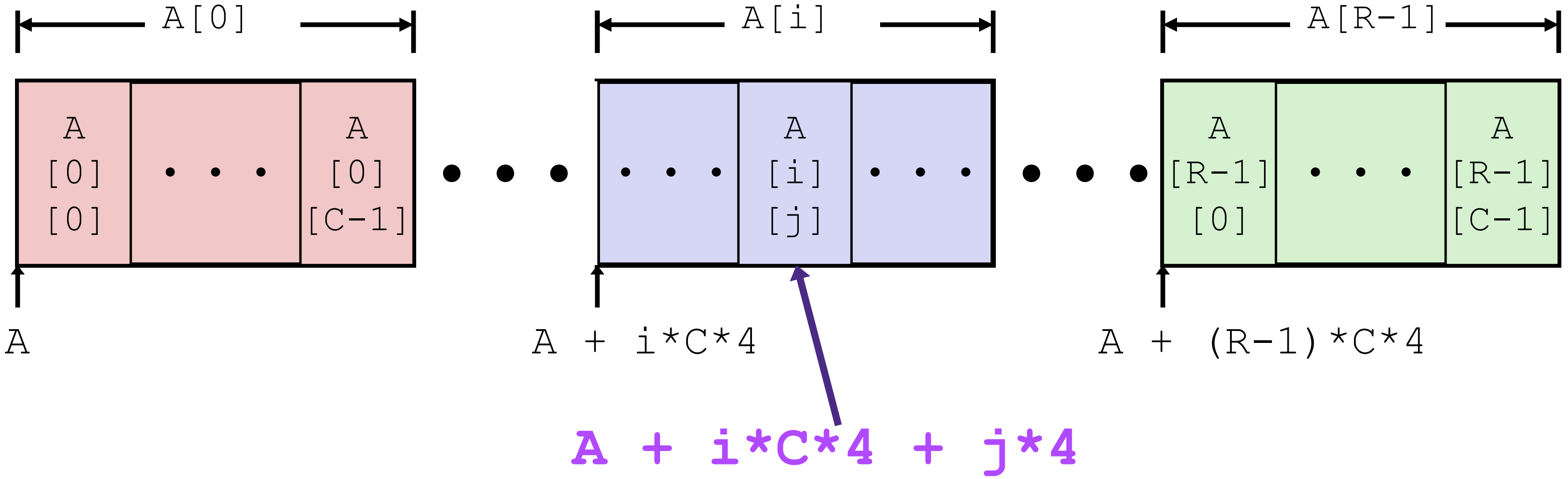


Nested Array Element Access

- 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

Multilevel Array Example

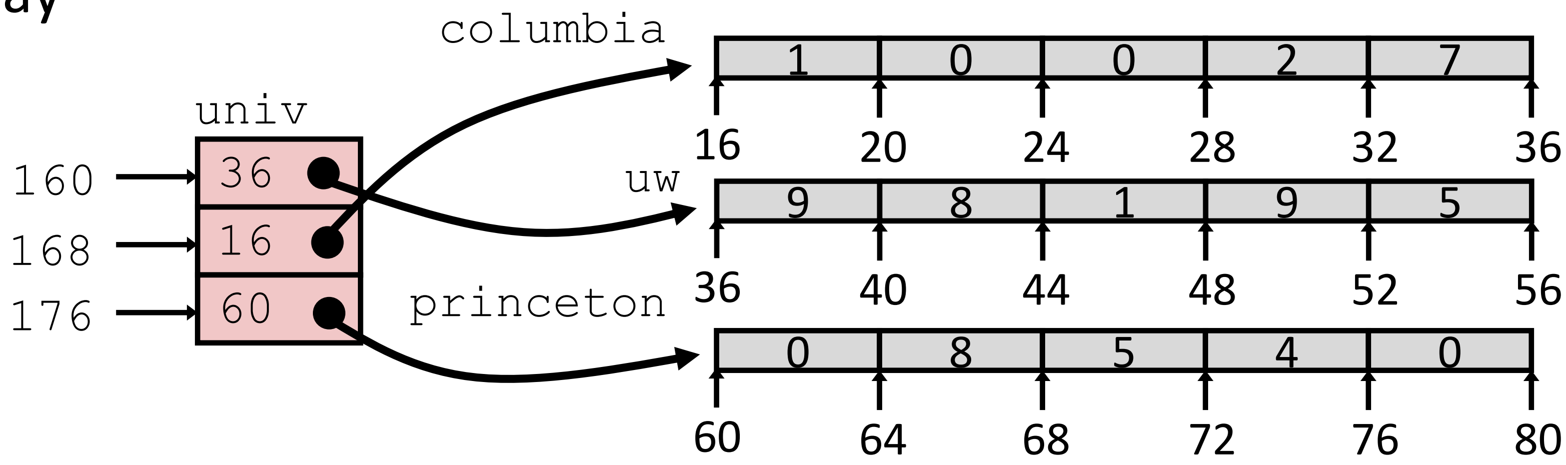
Note: this is how Java represents multidimensional arrays!

- Multilevel Array Declaration(s):

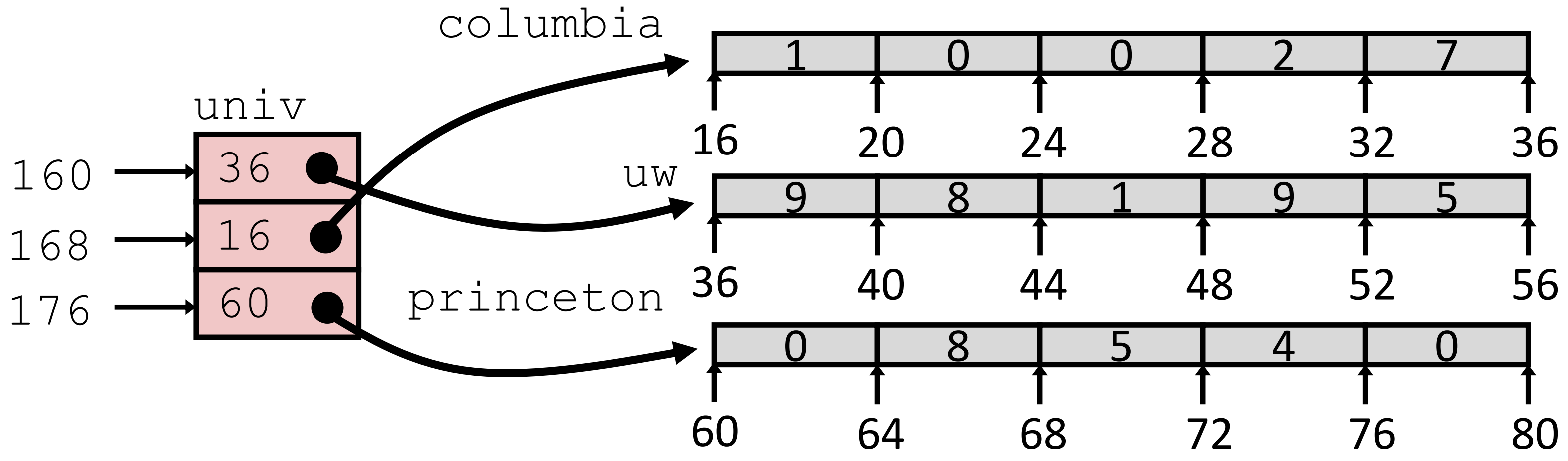
```
  int columbia[5] = { 1, 5, 2, 1, 3 };
        int   uw[5] = { 9, 8, 1, 9, 5 };
int princeton[5] = { 0, 8, 5, 4, 0 };
```

```
int* univ[3] = {uw, columbia, princeton};
```

  - 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



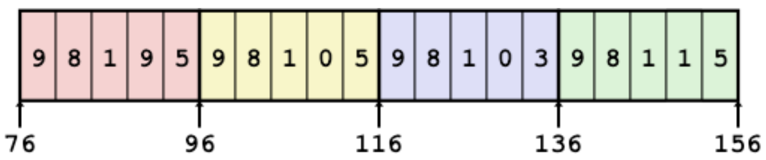

```
int get_univ_digit (int index, int digit) {
  return univ[index][digit];
}
```

- 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

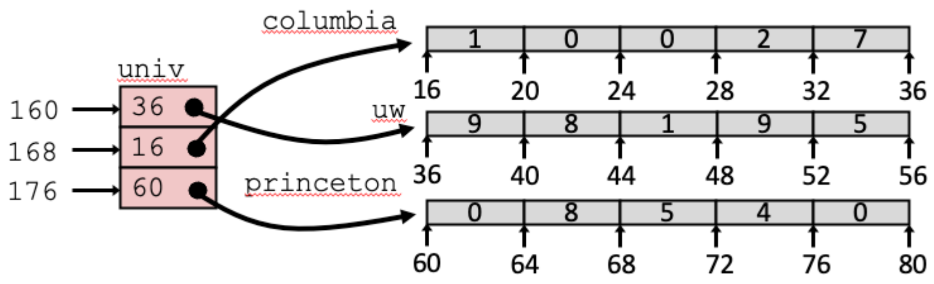
Multidimensional array:

```
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