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 <#>`)
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

❖ *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?
  ▪ Both pursue **efficiency** (*minimalism* is a means to an end)
Mainstream ISAs, Revisited

<table>
<thead>
<tr>
<th>Designer</th>
<th>Intel, AMD</th>
<th>University of California, Berkeley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
<td>16-bit, 32-bit and 64-bit</td>
<td>32 · 64 · 128</td>
</tr>
<tr>
<td>Introduced</td>
<td>1978 (16-bit), 1985 (32-bit), 2003 (64-bit)</td>
<td>2010</td>
</tr>
<tr>
<td>Design Type</td>
<td>CISC</td>
<td>RISC</td>
</tr>
<tr>
<td>Encoding</td>
<td>Variable (1 to 15 bytes)</td>
<td>Load-Core</td>
</tr>
<tr>
<td>Branching</td>
<td>Condition code</td>
<td>Variable</td>
</tr>
<tr>
<td>Endianness</td>
<td>Little</td>
<td>Little[1][3]</td>
</tr>
</tbody>
</table>

- **x86**
- **ARM**
- **RISC-V**

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

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

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

Does anything feel “off” about this landscape?
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)

- 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)
  Assembler (gcc -c or as)
  Object program (p1.o p2.o)
  Executable program (p)
```

Compiler (gcc -Og -S)
Assembler (gcc -c or as)
Linker (gcc or ld)
Static libraries (.a)
Loader (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

- Super complex, whole courses devoted to these!

- Compiler optimizations
  - “Level” of optimization specified by capital ‘O’ flag *(e.g., `-Og`, `-O3`)*
Compiling Into Assembly (Review)

- **C Code (sum.c)**
  
  ```c
  void sumstore(long x, long y, long *dest) {
    long t = x + y;
    *dest = t;
  }
  ```

- **x86-64 assembly (gcc -Og -S sum.c)**
  
  ```assembly
  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](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
  - *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
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](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>:
400536:   48 01 fe  add %rdi,%rsi
400539:   48 89 32  mov %rsi,(%rdx)
40053c:   c3  retq
```

❖ **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 \( N \)
- \textbf{Contiguously} allocated region of \( N \times \text{sizeof}(T) \) 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];)
```

```
x x + 12  
x + 4 x + 8 x + 12 x + 16 x + 20  
x x + 8 x + 16  
x x + 8 x + 16 x + 24  
x x + 8 x + 16 x + 24
```
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];
```

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x[4]</td>
<td>int</td>
<td>5</td>
</tr>
<tr>
<td>x</td>
<td>int*</td>
<td>a</td>
</tr>
<tr>
<td>x+1</td>
<td>int*</td>
<td>a + 4</td>
</tr>
<tr>
<td>&amp;x[2]</td>
<td>int*</td>
<td>a + 8</td>
</tr>
<tr>
<td>x[5]</td>
<td>int</td>
<td>?? (whatever’s in memory at addr x+20)</td>
</tr>
<tr>
<td>*(x+1)</td>
<td>int</td>
<td>7</td>
</tr>
<tr>
<td>x+i</td>
<td>int*</td>
<td>a + 4*i</td>
</tr>
</tbody>
</table>
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 };

- 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:

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

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

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

  **BAD!**

  ```c
  int* ar
  ```

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

  Must explicitly pass the size!
Data Structures in C

❖ **Arrays**
  - One-dimensional
  - Multidimensional (nested)
  - Multilevel

❖ **Structs**
  - Alignment

❖ **Unions**
Nested Array Example

```c
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 is the layout in memory?

Remember, \( T \ A[\pi] \) is an array with elements of type \( T \), with length \( \pi \).
Nested Array Example

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

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

Remember, \( T \ A[N] \) is an array with elements of type \( T \), with length \( N \).
Two-Dimensional (Nested) Arrays

- Declaration: \( T \ A[R][C]; \)
  - 2D array of data type \( T \)
  - \( R \) rows, \( C \) columns
  - Each element requires \( \text{sizeof}(T) \) bytes

- Array size?

\[
\begin{bmatrix}
A[0][0] & \cdots & A[0][C-1] \\
\vdots & \ddots & \vdots \\
A[R-1][0] & \cdots & A[R-1][C-1]
\end{bmatrix}
\]
Two-Dimensional (Nested) Arrays

- Declaration: \( T \ A[R][C]; \)
  - 2D array of data type \( T \)
  - \( R \) rows, \( C \) columns
  - Each element requires \( \text{sizeof}(T) \) bytes

- Array size:
  - \( R \times C \times \text{sizeof}(T) \) bytes

- Arrangement: **row-major** ordering

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

```
\begin{array}{cccc}
A[0][0] & \cdots & A[0][C-1] \\
\vdots & \ddots & \vdots \\
A[R-1][0] & \cdots & A[R-1][C-1]
\end{array}
```

Every byte between these addresses is part of \( A \).
Nested Array Row Access

❖ Row vectors

- Given \( T \ A[R][C] \),
  - \( A[i] \) is an array of \( C \) elements ("row \( i \)") \( \rightarrow \) just an address!
  - \( A \) is address of array
  - Starting address of row \( i = A + i \times (C \times \text{sizeof}(T)) \)

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

\( A \)

\( C \times 4 \) bytes wide

\( A[0] \)

\( A[0][0] \)

\( A[0][C-1] \)

\( A+i \times C \times 4 \)

\( A[R-1][0] \)

\( A[R-1][C-1] \)

\( A+(R-1) \times C \times 4 \)
Nested Array Element Access

- Array Elements
  - $A[i][j]$ is element of type $T$; let $\text{sizeof}(T) = t$ bytes
  - Address of $A[i][j]$ is $$(A + i \times C \times \text{sizeof}(T)) + j \times \text{sizeof}(T)$$

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

```
A[0] [0] [C-1]
A
```
```
A[i] [i] [j]
A + i*C*4
```
```
A[R-1] [R-1] [C-1]
A + (R-1)*C*4
```
Nested Array Element Access

- **Array Elements**
  - $A[i][j]$ is element of type $T$; let $\text{sizeof}(T) = t$ bytes
  - Address of $A[i][j]$ is
    $$A + i \times (C \times t) + j \times t = A + (i \times C + j) \times t$$

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

![Diagram showing element access in a nested array]
Data Structures in C

❖ Arrays
  ▪ One-dimensional
  ▪ Multidimensional (nested)
  ▪ Multilevel

❖ Structs
  ▪ Alignment

❖ Unions
Multilevel Array Example

- **Multilevel Array Declaration(s):**
  ```java
  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 `ints`**
  - *Could* have inner arrays of different lengths!

**Note:** this is how Java represents multidimensional arrays!
Multilevel Array Element Access

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

```c
int get_univ_digit (int index, int digit) {
    return univ[index][digit];
}
```
Array Element Accesses

Multidimensional array:

```c
int get_sea_digit (int index, int digit)
{
    return sea[index][digit];
}
```

Multilevel array:

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

- **Accesses *look* the same, but aren’t:**
  \[ \text{Mem[sea+20*index+4*digit]} \neq \text{Mem[univ+8*index]+4*digit} \]

- **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