CSC2/452 Computer Organization
More Arrays, Pointers

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URCS

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Outline

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Recap

More on Arrays

Strings

Multidimensional Arrays

Function Pointers

Structures and Unions
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Assignments and Homeworks

- Assignment #2 still being baked
- Homework 5 will land on Wednesday as usual
Pointers

- C’s abstraction of addresses
- Declared as `sometype *var`
  - Indicates `var` is a pointer to `sometype`
  - Tracks size of data in addition to address
- You modify pointers (i.e. `var`) by treating them as ordinary variables
  - Assignment, `var = &varofsometype`
  - Pointer arithmetic, `var = var + 1` (but `1` is internally multiplied by size of `sometype`)
- You read/write the data pointed to by a pointer using indirection operator (*)
  - `var2ofsometype = *var`, which assigns the value `varofsometype` to LHS
  - Also called dereferencing
- Primarily used in C for
  - Passing arguments for modification by function
  - Arrays, which are just pointers under the hood
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Today on Arrays

- Stack-allocated arrays
  - local variables that are arrays
  - limited in size
- One-dimensional arrays
  - What about storing matrices?
- Today:
  - heap-allocated arrays (essentially unlimited)
  - multidimensional arrays
Memory Allocators

- Memory on a system is a (finite) resource
- Must be distributed among programs
- Need something that tracks who “owns” a particular piece of memory
- This something is called a *memory allocator*
- There are many memory allocators in a system
  - Kernel (or System Allocator)
  - Runtime library allocator
  - Custom application allocators
- You will build a memory allocator later in the course...
Memory Allocator

Usually, supports 3 functions:

- allocation: to obtain a region of memory
- free: to release the region of memory
- reallocation: usually to resize a region of memory
Stack Allocation

We have already seen stack frame creation in previous lectures:

- Creating a stack frame: allocating memory on the stack
  - sub from %esp
- Destroying a stack frame: freeing memory on the stack
  - add to %esp
- Note, both operations really only supported at top of stack

Stack allocators are a special case of *bump* allocators.

- Only allocate at one end of a memory region
- Use add/sub to allocate/free memory
- Not very sophisticated, but very fast
C Runtime Allocator

The C standard library supports the following heap allocators, all require including stdlib.h:

- `malloc`: allocate memory of a certain size
- `calloc`: allocate memory and zero it
- `realloc`: change size of memory (may move data)
- `free`: free memory allocated by the above functions

- All allocators return a pointer to the newly allocated region of memory or NULL if they fail.
Heap allocation

- The heap is a region of memory like the stack
  - But grows towards higher addresses (unlike the stack)
- Data stored in the heap is accessible to the entire program
  - Anybody who has the pointer to the data can access it
- Heap data is only freed automatically when your program exits
  - You must manually free heap data you no longer want
  - Otherwise your program could run out of memory
Garbage collection

- Keeping track of memory that is no longer needed and freeing it is very tedious
  - Mistakes lead to difficult to track down bugs
- Most languages now use a technique called “garbage collection” (GC)
  - Automatically detects which regions of memory are no longer being used
  - Java, Go, JavaScript, Python, etc.
  - Tends to be unpredictable, and can cause performance issues
- C does not support GC by default
#include <stdlib.h>

void *malloc(size_t size);
void free(void *ptr);
void *calloc(size_t nmemb, size_t size);

int *p;

// allocate 1000 ints, note size is size in bytes
p = (int *) malloc(1000 * sizeof(int));

// --- OR --- //

// or allocate 1000 ints initialized to zero
p = (int *) calloc(1000, sizeof(int));

// free allocated memory
free(p);

The sizeof C operator returns the size of the type
Allocating an array on the heap

```c
int *alloc_and_init_array(int N) {
    int *x;

    x = (int *) malloc(N * sizeof(int))

    // initialize it
    for(int i = 0; i < N; i++) {
        x[i] = i*i;
    }

    return x;
}
```

- Note we’re returning the value of `x`
  - i.e. the address in `x`, not the address of `x`
- Since the address is on the heap, it is independent of the function call
- You can treat pointers to the heap as any other pointer
Summary of Memory Allocation

- Call `malloc` (or `calloc`) when you need memory
  - Obtain a pointer to the memory region
- Use the pointer to read/write to the memory region
- Call `free` on the pointer when you no longer need it
Common Bugs using Dynamic Memory

- Memory leaks
  - When you lose the pointer to an allocated region of memory
  - Can’t be freed until program exits
  - “harmless”, program just consumes more and more memory as it runs

- Reading uninitialized memory
  - Memory from malloc should be initialized before reading it

- Out-of-bound accesses
  - Deferencing a pointer that points outside the allocated region
  - Undefined behaviour!

- Use-after-free
  - Attempt to access memory region after free
  - Essentially a dangling pointer pointing to the heap
  - Dangerous!

- Double-frees
  - Trying to call free on the same pointer twice
  - Undefined behaviour!
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Strings in C

- Strings in C are just character arrays
  - char *c is a string
  - as are char c[10], unsigned char, etc.
  - also types uint8_t and int8_t

- C does not track array length
  - So by convention, strings end with a NUL character (note the single L)
  - NUL is a unprintable (and untypeable character)
Specifying unprintable characters

- ASCII characters 0 to 31 are non-printable characters
  - 0x9 is TAB
  - 0xa is LINEFEED/LF (move to next line)
  - 0xd is CARRIAGE RETURN/CR (return to head of line in a printer)
  - 0xc is FORM FEED (eject page out of printer)
- Among these you will encounter NUL (0x0), TAB (0x9), LF (0xa), CR (0xd)
  - You type these as '\0' (NUL), '\t' (TAB), '\n' (LF), '\r' (CR)
  - These are called escape sequences
int main(void) {
    // C automatically puts a \0 at the end
    // length of array is also automatically calculated

    char greeting[] = "hello World\n";

    greeting[0] = 'H';    // note character literals use apostrophes
}
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Memory vs Arrays

- Memory is (logically) one-dimensional
  - addresses go from 0 to $2^n - 1$, for some $n$
- 1-D arrays map naturally to memory
- What about higher-dimensional arrays?
  - 2-D, i.e. matrices
  - higher-dimensions, “tensors”
The problem

- For 1-D
  - \(a[i]\) translates to memory address \(a + i\)

How do we translate an 2-D array index \((i, j)\), where \(i\) indicates row, and \(j\) indicates column?

- Assume number of rows is \(r\) and columns is \(c\)
Row-major ordering

| a  b  c  d  |
| e  f  g  h  | => [ a  b  c  d  e  f  g  h  i  j  k  l ]
| i  j  k  l  |

- Index \((i, j)\) is translated to \(j + i \times c\)
  - Here \(r = 3\) and \(c = 4\)
- All elements of the same row are laid out next to each other in memory
float *m;
int R = 3, C = 4;

m = (float *) malloc(R * C * sizeof(float))

for(int i = 0; i < R; i++) {
    for(int j = 0; j < C; j++) {
        m[j + i * C] = 1.0;
    }
}
## Column-major ordering

| a b c d |
| e f g h | => [ a e i b f j c g k d h l ]
| i j k l |

- Index \((i, j)\) is translated to \(i + j \times r\)
  - Here \(r = 3\) and \(c = 4\)
- All elements of the same column are laid out next to each other in memory
Column-major ordering in C

```c
float *m;
int R = 3, C = 4;

m = (float *) malloc(R * C * sizeof(float))

for(int i = 0; i < R; i++) {
    for(int j = 0; j < C; j++) {
        m[i + j * R] = 1.0;
    }
}
```
For index \((i, j, k)\) in space with dimensions \((x, y, z)\)
- Linear address: \(k + j \times z + i \times y \times z\)
- Note: knowledge of the size of dimension of index \(i\) is not necessary
C supports syntax like `A[i][j]` for statically allocated arrays
  - Sizes must be specified at compile-time
  - C99 makes this more flexible, see the textbook for details

Such arrays are always in row-major order

Since the compiler translates addresses for you
  - And C doesn’t track dimensions of arrays
  - You must always specify all dimensions except last when passing these arrays as parameters, if you want to use them

```c
int a[10][2];

void sum(int m[][2]) {
}
```
Arrays of Pointers

```c
int *a[10];

for(i = 0; i < 10; i++) {
    a[i] = (int *) malloc(2*sizeof(int)); // fixed
}

for(i = 0; i < 10; i++) {
    for(j = 0; j < 2; j++) {
        a[i][j] = i + j;
    }
}

▶ Don't confuse this with int a[10][2]
▶ This is commonly written as int **a
▶ This is an array of pointers
▶ The previous was an array of ints
▶ But this is another, C-specific idiom to emulate multi-dimensional arrays
```
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Addresses of Data vs Addresses of Code

- In assembly, labels are addresses
- Labels can indicate both data and code
  - Naturally, since both data and code are in memory
- What about in C?
Function Pointers

- C allows function pointers
- But must store more information than just address of function
  - Parameters and their types
  - Return type of function
Syntax

```c
int sum(int a, int b);

▶ sum takes two int parameters
▶ sum is a function returning an int
▶ How shall we declare a variable to points to sum?
```
Try #1

```c
int *v;

- We’re trying to make \( v \) a pointer to sum
- This is a pointer to an \( \text{int} \)
- Also lacks information about parameters
```
Try #2: Adding parameter information

```c
int *v(int a, int b);
▷ This now contains parameter info
  ▷ Can clearly see this is not a pointer to int
▷ But, can this be confused for a function returning a int pointer?
```
Try #3: Disambiguating function pointers from function declarations

```c
int (*v)(int a, int b);
```

- This contains parameter info
  - Can clearly see this is not a pointer to `int`
- The `(*v)` indicates that `v` is a pointer to function
- And the function that `v` points to returns an `int`
Using function pointers

#include <stdio.h>

int sum(int a, int b) {
    return a + b;
}

int main(void) {
    int (*v)(int a, int b);
    v = sum;
    printf("address of sum: %p\n", v);

    v(1, 2);
}

Output:
address of sum: 0x556bfef3964a

- No & required (though it can be used)
- No * required (though it can be used)
  - (*v)(1, 2), watch precedence
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Record Types

```c
struct point {
    float x;
    float y;
};

struct point pt;
struct point pts[10];
struct point *polygon;
```

- struct holds multiple values
- Each field of struct has a name
- struct can be nested
Recursive structures

```c
struct node {
    int value;
    struct node *left;
    struct node *right;
};
```

- This is a *recursive* structure
  - Possibly from a binary tree
- The “self-references” must be pointers
struct interactions with pointers

struct node {
    int value;
    struct node *left;
    struct node *right;
};

struct node *head;

Which of these accesses head’s right node?

*head.right

(*head).right
The -> operator

```c
struct node {
    int value;
    struct node *left;
    struct node *right;
};

struct node *head;
```

Since field access (.) has higher precedence than deference, you must use (*head).right.

- Alternative: head->right, which has same precedence as .
#include <stdio.h>

struct node {
    int value;
    struct node *left;
    struct node *right;
};

int main(void) {
    printf("%d\n", sizeof(struct node));
}

Output (on a LP64 system)?

- 20
- 24
- 32
Structure Memory Layout

Tight packing:

<table>
<thead>
<tr>
<th>value</th>
<th>left</th>
<th>right</th>
</tr>
</thead>
<tbody>
<tr>
<td>0123</td>
<td>01234567</td>
<td>01234567</td>
</tr>
</tbody>
</table>

Packing with “holes” (also called padding)

<table>
<thead>
<tr>
<th>value</th>
<th>left</th>
<th>right</th>
</tr>
</thead>
<tbody>
<tr>
<td>0123</td>
<td>0123</td>
<td>01234567</td>
</tr>
</tbody>
</table>

- Structure layout in memory is implementation defined
- Usually:
  - Struct size is a multiple of largest field
  - Each individual field is naturally aligned
Like struct, union contains fields

However, all fields in a union overlap in memory
  ▶ At most one contains valid data
Union Memory Layout

This union occupies 8 bytes of memory
- The size of its largest field
- But all fields overlap
  - Writing to one changes the others as well
- Writing to one field, and reading that data through another field is allowed
  - But it is implementation-defined
Summary

- Seen how C is implemented at machine level
  - Variables, Expressions
  - Conditionals, Loops
  - Functions
  - Pointers, Structures and Unions
- Every program executes a stream of assembly instructions
  - If you know the assembly instructions you know what is happening