Structures and Allocation

CSE 220: Systems Programming

Ethan Blanton & Carl Alphonce

Department of Computer Science and Engineering

University at Buffalo

Effective Questions

For programming questions, ask:

- What did I do?
- What did I expect to happen?
- What actually happened?
- How are they different?

You must know what you expected to identify the problem!

When asking us questions, tell us what you did, what you expected, and what you got.

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Building Complex Applications

Building more complex applications frequently requires:

- Data structures, including self-referential structures
- Allocation of memory at program run time

Structures are provided by the C language.

Memory allocation is provided by the C library.

Structures

A C `struct` aggregates multiple data items into one value.

These items are called members.

The aggregate is a new (`struct`) type.

The members of a structure are stored together.

Self-referential structures can form linked lists, *etc.*

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Memory Allocation

The amount of memory used by complex data may not be known at compile time.

Solving this requires memory allocation.

Self-referential structures like lists are normally allocated.

Allocation and release of memory in C is manual.

This makes C memory efficient, but also prone to leaks.

The C Struct

A `struct` is a compound data type consisting of one or more other types.

```
struct IntList {
    int             value;
    struct IntList *next;
};
```

This struct contains an integer and a pointer.

`value` and `next` are called members of the structure.

Any variable of type `struct IntList` contains both of these members.

Declaring and Using Structures

The syntax for structure declaration is

```
struct StructureTypeName {
    // Members in structure
    // Each member has a type and a name
} varname; // semicolon required!
```

An instance of the structure may be created where the structure is declared, or using the type name later:

```
struct StructureTypeName varname;
```

Accessing Structure Members

The . operator is used to access the members of a structure.

```
struct IntList node = { 7, NULL };
node.value = 3;
```

Any member of a structure can be accessed with .:

```
struct Complex {
    double real, im;
};
struct ComplexList {
    struct Complex complex;
    struct ComplexList *next;
} complexlist;
complexlist.complex.real = 0.0;
```

Structure Pointers

The . operator is cumbersome for structure pointers:

```
struct IntList *list = get_list_pointer();
(*list).next = NULL;
```

The -> operator is syntactic sugar for (*).:

```
list->next = NULL;
```

The -> operator can be used to access any member of a structure via a pointer to the structure type.

Operations on Structures

A structure value:

- Can have its address taken with &
- Can be copied with =
- Can be used to access a member with .

A structure pointer:

- Can do all the things any pointer can do
- Can be used to access a member with ->

No other operations on structures are legal!

Aside: The sizeof operator

There are several operators used to help with reflection in C.

One of these is the `sizeof` operator.

It returns the size in bytes of its operand, which can be:

- A variable
- An expression that is “like” a variable
- A type

(Expressions “like” a variable include, *e.g.*, members of structures.)

Looking at sizeof

Examples:

```
void func(int matrix[2][3]) {
    double dist;

    sizeof(int);                // yields 4
    sizeof(dist);               // yields 8
    sizeof(matrix);             // yields ... 8?
}
```

Note that sizeof arrays is not reliable.

Only arrays declared within the current scope will be correct.¶

We will discuss the sizes of things in more detail, later.

The void * type

The type `void *` is used to indicate a pointer of unknown type.

You may recall that `void` indicates a meaningless return value.

`void *` is treated specially by the C compiler and runtime:

- A `void *` variable can store any pointer type
- Type checks are mostly bypassed assigning to/from `void *`
- Any attempt to dereference a `void *` pointer is an error

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Pointer Assignments

Consider the following:

```
int i;
double d;
int *pi = &i;
double *pd = &d;
```

Each of these pointers is typed. These are errors:

```
pi = pd;
pd = pi;
```


©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Pointer Assignments

Consider the following:

```
int i;
double d;
int *pi = &i;
double *pd = &d;
```

This is where it gets dangerous:

```
void *p = pi;
pd = p;
```

This is perfectly legal.

(What does it mean?)

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

The Standard Allocator

The C library contains a standard allocator.

With this allocator you can request memory from the system.

Allocated memory is identified by its address.

Requesting Memory

Memory is requested using malloc() or calloc():

```
void *malloc(size_t size);
void *calloc(size_t nmemb, size_t size);
```

malloc accepts:

- A size_t size in bytes

calloc accepts:

- A size_t number of members of an array
- A size_t size in bytes of each member

Both return a void * pointer to usable memory.

calloc() sets all bytes in the memory to zero.

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Allocation Sizes

It is impossible to tell how much memory a pointer "points to."

The allocator returns at least as much as the user requested.

If you need to know how much that was, you need more information!

Typically:

- From a variable or argument (*e.g.*, `argc`)
- From a member in a struct (*e.g.*, `nprios` in PA2)
- Using knowledge of the data (*e.g.*, `strlen()` on a string)

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Allocating a Structure

As an example, let's allocate a structure:

```
struct IntList *get_list_pointer() {
  struct IntList *head = calloc(1, sizeof(struct
     IntList));
  return head;
}
```

Note that:

- The integer in head is set to 0
- The next pointer in head is set to NULL

Allocating an Array

We can also allocate arrays.

```
malloc(10 * sizeof(int));      // Array of 10 ints

calloc(10, sizeof(int));       // Array of 10 ints
```

In C, an array is just multiple data items adjacent in memory!

Freeing Memory

C has no garbage collector.

The programmer is responsible for freeing memory after use.

The function `free()` does this:

```
void free(void *ptr);
```

Free accepts:

- A pointer allocated by `malloc()`, `calloc()`, or `realloc()`

Once a pointer is freed, that pointer must not be used again.

Failed allocations

Allocations can fail.

A failed allocation will return `NULL`.

On a modern machine, this *usually* means an unreasonable allocation.

E.g., you accidentally allocated 2 GB instead of 2 KB.

On smaller systems, failed allocations are normal.

Often you can't do much about a failed allocation, of course.

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

Use-after-free

A common class of error is use-after-free.

This is when a freed pointer is used.

This is particularly dangerous, because the allocator may reuse that pointer.

Therefore, it is:

- Pointing to usable memory
- Not valid
- Likely to corrupt data!

Setting free'd pointer variables to `NULL` can help prevent this.

Out-of-bounds access

Because heap allocations have no obvious size, out-of-bounds access is easy.

```
int *array = malloc(2 * sizeof(int)); /* int[2]   */
for (int i = 0; i <= 2; i++) {        /* 0, 1, 2! */
    array[i] = 0;                     /* Illegal  */
}
```

The compiler will not catch this.

Summary

- Structs are a collection of values.
- Structs can be self-referential.
- The C standard library contains a flexible allocator.
- Standard allocator allocations are sized by the programmer.
- C does not provide a way to query the size of an allocation.

©2024 Ethan Blanton & Carl Alphonce / CSE 220: Systems Programming

References I

Required Readings

[1] Brian W. Kernighan and Dennis M. Ritchie. *The C Programming Language*. Second Edition. Chapter 2: 2.7; Chapter 6: Intro, 6.1–6.7. Prentice Hall, 1988.

[2] Linux man-pages project. `man 3 malloc`.

License

Copyright 2024 Ethan Blanton, All Rights Reserved.
Copyright 2022–2024 Carl Alphonce, All Rights Reserved.
Copyright 2019 Karthik Dantu, All Rights Reserved.

Reproduction of this material without written consent of the author is prohibited.

To retrieve a copy of this material, or related materials, see `https://www.cse.buffalo.edu/~eblanton/`.