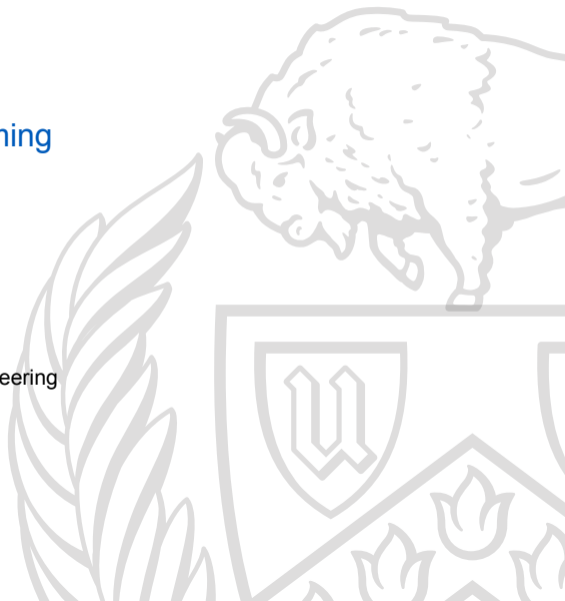


Memory Allocation

CSE 220: Systems Programming

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Allocating Memory

We have seen how to use pointers to address:

- An existing variable
- An array element from a string or array constant

This lecture will discuss [requesting memory from the system](#).

Memory Lifetime

All variables we have seen so far have **well-defined lifetime**:

- They persist for the entire life of the program
- They persist for the duration of a single function call

Sometimes we need **programmer-controlled** lifetime.

Examples

```
int global;           /* Lifetime of program */

void foo() {
    int x;           /* Lifetime of foo() */
}
```

Here, `global` is **statically allocated**:

- It is allocated by the compiler
- It is created when the program starts
- It disappears when the program exits

Examples

```
int global;           /* Lifetime of program */

void foo() {
    int x;           /* Lifetime of foo() */
}
```

Whereas `x` is **automatically allocated**:

- It is allocated by the compiler
- It is created when `foo()` is called ¶
- It disappears when `foo()` returns

Effective Questions

Answering questions is easy.

Asking the right question is hard!

For conceptual problems, ask:

- What do I **have**?
- What do I **need**?
- Can I figure out how to get from here to there?
- What about **partway there**?

If you need help, tell us (in your words!) what you have and what you need!

The Heap

The **heap** represents memory that is:

- allocated and released **at run time**
- managed **explicitly by the programmer**
- **only obtainable** by address

Heap memory is **just a range of bytes** to C.

Memory from the heap is **given a type** by the programmer.

We will see **much more** about the heap later!

Heap Allocations

Each allocation from the heap is **represented by a pointer**.

Each allocation has a **fixed size**.

This size is declared **at allocation time**.

Accesses outside of the allocation **must not be made** using the returned pointer!

Releasing Memory

Memory can be **released** back to the heap.

This memory can then be used for **future heap allocations**.

It can potentially (**but often is not**) be returned to the OS.

Memory that has been released **must not be accessed again**.

The C language **will not detect** accesses to released memory!

void *

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:

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

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;
```

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?)

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:

```
char str[32];  
int matrix[2][3];
```

```
sizeof(int);           // yields 4  
sizeof(str);          // yields 32  
sizeof(matrix);       // yields 24
```

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 Standard Allocator

The C library contains a [standard allocator](#).

```
#include <stdlib.h>
```

```
void *malloc(size_t size);
```

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

```
void *realloc(void *ptr, size_t size);
```

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

These functions allow you to:

- [Request memory](#) (`malloc()`, `calloc()`, `realloc()`)
- [Release memory](#) (`free()`)

Allocating

The allocating functions `request memory` in slightly different ways.

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

All three `return a non-null void pointer` on success.

All three `return NULL` on failure.

malloc()

```
void *malloc(size_t size);
```

Malloc returns a `void *` pointer, which can point to [anything](#).

It allocates [at least](#) size bytes.

size is often the result of a `sizeof()` expression.

To allocate an [integer](#):

- Determine the size of an `int`
- Request enough memory to hold one

```
int *pi = malloc(sizeof(int));
```

Allocating an array

To allocate an array with 10 `int` entries dynamically, we:

- Determine the size of a single `int`
- Tell the system we want ten of those
- Assign the result to an appropriate pointer

```
int *array = malloc(10 * sizeof(int));
```

The variable `array` can now be used as a regular `int` array.

calloc()

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

The closely-related `calloc()` allocates **cleared memory**.

The memory returned by `malloc()` is **uninitialized**.

The memory returned by `calloc()` is set to **bitwise zero**.

Note that invocation is slightly different!

realloc()

```
void *realloc(void *ptr, size_t size);
```

Allocation sizes are **fixed**, but you can **request a resize**.

realloc() will attempt to **change the size** of an allocation.

If it cannot, **it may create a new allocation** of the requested size.

Normal usage is:

```
ptr = realloc(ptr, newsize);
```

This handles the case where the **resize is not possible**.

free

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

Free accepts a `void *` pointer, which can point to anything.

Freed memory returns to the system to be allocated again later via `malloc()`.

```
free(array);
```

Note that `free` **does not modify the value of its argument**. Thus you cannot “tell” that a pointer has been freed!

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.

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 pointers 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
        access */
}
```

The compiler **will not catch this**.

Practice Example 1

```
1 int a[2];
2 int *b = malloc(2 * sizeof(int));
3 int *c;
4
5 a[2] = 5;
6 b[0] += 2;
7 c = b + 3;
8 free(&(a[0]));
9 free(b);
10 free(b);
11 b[0] = 5;
```

Where are the errors?

1. Line 5
2. Line 6
3. Line 8
4. Line 10

Practice Example 2

```
1 int a[2];
2 int *b = malloc(2 * sizeof(int));
3 int *c;
4
5 a[2] = 5;
6 b[0] += 2;
7 c = b + 3;
8 free(&(a[0]));
9 free(b);
10 free(b);
11 b[0] = 5;
```

Where is the first **guaranteed** error?

1. Line 5
2. Line 6
3. Line 8
4. Line 10

Summary

- The heap is where you manually allocate memory.
- The C standard library contains a flexible allocator.
- Heap allocations are sized by the programmer.

Next Time ...

- Integer properties
- Bit widths
- Integer representation

References I

Required Readings

- [1] Brian W. Kernighan and Dennis M. Ritchie. *The C Programming Language*. Second Edition. Chapter 2: 2.7. Prentice Hall, 1988.

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