CSE 333

Lecture 4 - malloc, free, struct, typedef

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New exercise out today, due before class Wednesday

Exercise grading: 3 means almost absolutely perfect; 2 means good but some small flaws. We expect 2’s to be (much?) more common than 3’s, particularly at first.

We cut a fair amount of slack on ex0, ex1 for picky style things, but use clint.py to check from now on & ask if something seems off base

HW0 due tonight, 11 pm

Be sure to add/commit/push, then tag with hw0-final, then push tag

Then clone the repo into somewhere completely different, do git checkout hw0-final, and verify that all is well
HW1 pushed to GitLab repos on Friday, due Thur. 4/14

You might get a “merge conflict” when pushing HW0. Do a pull, accept the merge (ok to use the default message), then do git add/commit/push

Suggestion: look at example_program_{ll|ht}.c for typical usage of lists & hash tables

HW1 (and all future): you **may not** modify interfaces (.h files)

Often true in “real life” — or at least assume that is the rule unless told otherwise

Problems? Questions? Use the discussion board so all can benefit
We *highly* recommend doing the exercises that are at the end of each lecture.

also, Google for “C pointer exercises” and do as many as you can get your hands on.

you MUST master pointers quickly, or you’ll have problems for the rest of the course (not to mention HW1)
Double pointers

what’s the difference between a (char *) and a (char **)?

```c
int main(int argc, char **argv) {
    char hi[6] = {'h', 'e', 'l', 'l', 'o', '\0'};
    char *p, **dp;

    p = &(hi[0]);
    dp = &p;

    printf("%c %c\n", *p, **dp);
    printf("%p %p %p\n", p, *dp, hi);
    p += 1;
    printf("%c %c\n", *p, **dp);
    printf("%p %p %p\n", p, *dp, hi);
    *dp += 2;
    printf("%c %c\n", *p, **dp);
    printf("%p %p %p\n", p, *dp, hi);
    return 0;
}
```

Exercise 0: draw / update the box-and-arrow diagram for this program as it executes
Today’s goals:

- understand heap-allocated memory
  - malloc(), free()
- memory leaks
- quick intro to structs and typedef
Memory allocation

So far, we have seen two kinds of memory allocation:

```c
// a global variable
int counter = 0;

int main(int argc, char **argv) {
    counter++;
    return 0;
}
```

counter is **statically allocated**
allocated when program is loaded
deallocated when program exits

```c
int foo(int a) {
    int x = a + 1; // local var
    return x;
}
```

```c
int main(int argc, char **argv) {
    int y = foo(10); // local var
    return 0;
}
```
a, x, y are **automatically allocated**
allocated when function is called
deallocated when function returns
We need more flexibility

Sometimes we want to allocate memory that:

- persists across multiple function calls but for less than the lifetime of the program

- is too big to fit on the stack

- is allocated and returned by a function and its size is not known in advance to the caller

```c
// (this is pseudo-C-code)
char *ReadFile(char *filename) {
    int size = FileSize(filename);
    char *buffer = AllocateMemory(size);
    ReadFileIntoBuffer(filename, buffer);
    return buffer;
}
```
Dynamic allocation

What we want is *dynamically allocated memory*

- your program explicitly requests a new block of memory
  - the language runtime allocates it, perhaps with help from OS

Dynamically allocated memory persists until:

- your code explicitly deallocates it *manual memory management*
- a garbage collector collects it *automatic memory management*

C requires you to manually manage memory

- gives you more control, but causes headaches
C and malloc

variable = (type *) malloc(size in bytes);

malloc allocates a block of memory of the given size
returns a pointer to the first byte of that memory

malloc returns NULL if the memory could not be allocated

you should assume the memory initially contains garbage

you’ll typically use sizeof to calculate the size you need

// allocate a 10-float array
float *arr = (float *) malloc(10*sizeof(float));
if (arr == NULL)
    return errcode;
arr[0] = 5.1; // etc.
C and calloc

\[ \text{variable} = (\text{type }) \ast \text{calloc(howmany, \#bytes for each)}; \]

Like malloc, but also zeroes out the block of memory

helpful for shaking out bugs

slightly slower; preferred for non-performance-critical code

malloc and calloc are found in \texttt{stdlib.h}

// allocate a 10 long-int array
long *arr = (long *) calloc(10, sizeof(long));
if (arr == NULL)
    return errcode;
arr[0] = 5L;   // etc.
Deallocation

`free(pointer);`

Releases the memory pointed-to by the pointer

`pointer must` point to the first byte of heap-allocated memory

i.e., something previously returned by `malloc()` or `calloc()`

After `free()`’ing a block of memory, that block of memory might be returned in some future `malloc()` / `calloc()`

Some guidelines say you should set a pointer to `NULL` after freeing it

Useful defensive programming; required if variable definition comment says so

```c
long *arr = (long *) calloc(sizeof(long),10);
if (arr == NULL)
    return errcode;
// .. do something ..
free(arr);
arr = NULL;
```
Heap

The heap (aka “free store”) is a large pool of unused memory that is used for dynamically allocated data. `malloc` allocates chunks of data in the heap, frees data, and `malloc` maintains bookkeeping data in the heap to track allocated blocks.

<table>
<thead>
<tr>
<th>Address</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xFFFFFFFF</td>
<td>OS kernel [protected]</td>
</tr>
<tr>
<td></td>
<td>stack</td>
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<tr>
<td></td>
<td>shared libraries</td>
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<tr>
<td></td>
<td>heap (malloc/free)</td>
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<tr>
<td></td>
<td>read/write segment .data, .bss</td>
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<tr>
<td></td>
<td>read-only segment .text, .rodata</td>
</tr>
<tr>
<td>0x00000000</td>
<td></td>
</tr>
</tbody>
</table>
Heap + stack

```
#include <stdlib.h>

int *copy(int a[], int size) {
    int i, *a2;

    a2 = malloc(
        size * sizeof(int));
    if (a2 == NULL)
        return NULL;

    for (i = 0; i < size; i++)
        a2[i] = a[i];
    return a2;
}

int main(...) {
    int nums[4] = {2,4,6,8};
    int *ncopy = copy(nums, 4);
    // ... do stuff ...
    free(ncopy);
    return 0;
}
```

arraycopy.c
Heap + stack

```c
#include <stdlib.h>

int *copy(int a[], int size) {
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arraycopy.c

OS kernel [protected]

stack

main
argc, argv
nums 2 4 6 8
ncopy

copy
i    a2

heap (malloc/free)

read/write segment
globals

read-only segment
(main, f, g)
Heap + stack

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heap (malloc/free)

read/write segment

globals

read-only segment

(main, f, g)
Heap + stack

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heap (malloc/free)

read/write segment

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(main, f, g)
NULL

NULL: a guaranteed-to-be-invalid memory location

in C on Linux:

NULL is 0x00000000

an attempt to deference NULL causes a segmentation fault

that’s why setting a pointer NULL after you have free()’d it is useful defense (particularly if the pointer sticks around for a while)

it’s better to have a segfault than to corrupt memory!

```c
#include <stdio.h>

int main(int argc, char **argv) {
    int *p = NULL;
    *p = 1;  // causes a segmentation fault
    return 0;
}
```

segfault.c
Memory corruption

There are all sorts of ways to corrupt memory in C

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

int main(int argc, char **argv) {
    int a[2];
    int *b = malloc(2*sizeof(int)), *c;

    a[2] = 5;  // assign past the end of an array
    b[0] += 2; // assume malloc zeroes out memory
    c = b+3;  // mess up your pointer arithmetic
    free(&a[0])); // free() something not malloc()'ed
    free(b);
    free(b); // double-free the same block
    b[0] = 5;  // use a free()'d pointer

    // any many more!
    return 0;
}
```

memcorrupt.c
Memory leak

A memory leak happens when code fails to deallocate dynamically allocated memory that will no longer be used.

```c
// assume we have access to functions FileLen, 
// ReadFileIntoBuffer, and NumWordsInString.

int NumWordsInFile(char *filename) {
    char *filebuf = (char *) malloc(FileLen(filename)+1);
    if (filebuf == NULL)
        return -1;
    ReadFileIntoBuffer(filename, filebuf);

    // leak! we never free(filebuf)
    return NumWordsInString(filebuf);
}
```
Implications of a leak?

Your program’s virtual memory footprint will keep growing:

- for short-lived programs, this might be OK
- for long-lived programs, this usually has bad repercussions
  - might slow down over time (VM thrashing – see cse451)
  - potential “DoS attack” if a server leaks memory
  - might exhaust all available memory and crash
  - other programs might get starved of memory

in some cases, you might prefer to leak memory than to corrupt memory with a buggy free( )
Structured data

```c
struct tagname {
    type name;
    type name;
    ...
    type name;
};

struct Point {
    float x, y;
};

struct Point origin = {0.0, 0.0};
```

**struct**: a C type that contains a set of fields similar to a Java class, but without methods / constructors. Instances can be allocated on the stack or heap. Useful for defining new structured types of data.
Using structs

Use “.” to refer to fields in a struct

Use “->” to refer to fields through a pointer to a struct

```c
struct Point {  
    float x, y;
};

int main(int argc, char **argv) {  
    int i = 1;
    struct Point p1 = {0.0, 0.0}; // p1 is stack allocated
    struct Point *p1_ptr = &p1;

    p1.x = 1.0;
    p1_ptr->y = 2.0; // means same as (*p1_ptr).y = 2.0;
    return 0; // but better (i.e., expected) style
}
```

simplestruct.c
Copy by assignment

You can assign the value of a struct from a struct of the same type; this copies the entire contents

```c
#include <stdio.h>

struct Point {
    float x, y;
};

int main(int argc, char **argv) {
    struct Point p1 = {0.0, 2.0};
    struct Point p2 = {4.0, 6.0};

    printf("p1: {%f,%f}  p2: {%f,%f}\n", p1.x, p1.y, p2.x, p2.y);
    p2 = p1;
    printf("p1: {%f,%f}  p2: {%f,%f}\n", p1.x, p1.y, p2.x, p2.y);
    return 0;
}
```

structassign.c
typedef

typedef type name;

Allows you to define a new type whose name is name

especially useful when dealing with structs

// make "superlong" be a synonym for "unsigned long long"
typedef unsigned long long superlong;

// make "Point" be a synonym for "struct point_st { ... }"
typedef struct point_st {
    superlong x;
    superlong y;
} Point;

Point origin = {0, 0};
Dynamically allocated structs

You can malloc and free structs, as with other types

sizeof is particularly helpful here

typedef struct complex_st {
    double real;  // real component
    double imag;  // imaginary component
} Complex, *ComplexPtr;

ComplexPtr AllocComplex(double real, double imag) {
    Complex *retval = (Complex *) malloc(sizeof(Complex));
    if (retval != NULL) {
        retval->real = real;
        retval->imag = imag;
    }
    return retval;
}

complexstruct.c
structs as arguments

// Point is a (struct point_st)
// PointPtr is a (struct point_st *)
typedef struct point_st {
    int x, y;
} Point, *PointPtr, **PointPtrPtr;

void DoubleXBroken(Point p) {
    p.x *= 2;
}

void DoubleXWorks(PointPtr p) {
    p->x *= 2;
}

int main(int argc, char *argv) {
    Point a = {1,1};
    DoubleXBroken(a);
    printf("(%d,%d)\n", a.x, a.y);
    DoubleXWorks(&a);
    printf("(%d,%d)\n", a.x, a.y);
    return 0;
}

structarg.c
You can return structs

// a complex number is a + bi
typedef struct complex_st {
    double real; // real component (i.e., a)
    double imag; // imaginary component (i.e., b)
} Complex, *ComplexPtr;

Complex AddComplex(Complex x, Complex y) {
    Complex retval;
    retval.real = x.real + y.real;
    retval.imag = x.imag + y.imag;
    return retval; // returns a copy of retval
}

Complex MultiplyComplex(Complex x, Complex y) {
    Complex retval;
    retval.real = (x.real * y.real) - (x.imag * y.imag);
    retval.imag = (x.imag * y.real) - (x.real * y.imag);
    return retval;
}
Call by value or reference?

What if a function only needs to read a struct?

Call-by-value copies a struct, call-by reference copies a pointer

- Pointer copy is cheaper and takes less space unless struct is small
- Indirect field references through pointers are a bit more expensive, also can be harder for compiler to optimize because of pointer aliasing

For small things like complex numbers, call by value can be faster and is often preferred; for large structs use pointers

Similar issues for functions that return struct values

But be sure not to return dangling pointers!!!
Exercise 1

Write and test a program that defines:

- a new structured type Point
  represent it with floats for the x, y coordinate
- a new structured type Rectangle
  assume its sides are parallel to the x-axis and y-axis
  represent it with the bottom-left and top-right Points
- a function that computes/returns the area of a Rectangle
- a function that tests whether a Point is in a Rectangle
Exercise 2

```c
typedef struct complex_st {
    double real;  // real component
    double imag;  // imaginary component
} Complex;

typedef struct complex_set_st {
    int    num_points_in_set;
    Complex *points;          // an array of Complex
} ComplexSet;

ComplexSet *AllocSet(Complex c_arr[], int size);
void FreeSet(ComplexSet *set);
```

Implement `AllocSet()`, `FreeSet()`

`AllocSet()` needs to use `malloc` twice: once to allocate a new `ComplexSet`, and once to allocate the “points” field inside it.

`FreeSet()` needs to use `free` twice.
See you on Wednesday!