The Heap and Structs
CSE 333 Spring 2019

Instructor: Justin Hsia

Teaching Assistants:
Aaron Johnston       Andrew Hu       Daniel Snitkovskiy
Forrest Timour       Kevin Bi        Kory Watson
Pat Kosakanchit      Renshu Gu       Tarkan Al-Kazily
Travis McGaha
Administrivia

- **Piazza has a search bar** – use it *before* you post!
  - And make sure you name your posts descriptively so others can find them!

- Exercise 3 out today and due Wednesday morning

- We *highly* recommend doing the extra 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 trouble the rest of the course (including hw1)
Administrivia

- hw0 due tonight before 11:59 pm (and 0 seconds)
  - If your clock says 11:59, then it’s late!
    - You really, really don’t want to use late day tokens for hw0
  - Git: add/commit/push, then tag with hw0-final, then push tag
    - Then clone your repo somewhere totally different and do git checkout hw0-final and verify that all is well

- hw1 due Thursday, 4/18
  - You may not modify interfaces (.h files)
  - But do read the interfaces while you’re implementing them(!)
  - Suggestion: look at example_program_{ll|ht}.c for typical usage of lists and hash tables
Administrivia

- GitLab repo usage
  - Commit things regularly
    - Newly completed units of work, milestones, project parts, etc.
    - There shouldn’t be one massive commit the day hw is due
  - Provides backup – can retrieve old versions of files 😊
  - Don’t push . » and executable files or other build products (not portable)
Lecture Outline

- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks
- `structs` and `typedef`
Memory Allocation So Far

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

  - `counter` is *statically*-allocated
    - Allocated when program is loaded
    - Deallocated when process gets reaped

  - `a`, `x`, `y` are *automatically*-allocated
    - Allocated when function is called
    - Deallocated when function returns
Dynamic Allocation

- Situations where static and automatic allocation aren’t sufficient:
  - We need memory that persists across multiple function calls but not the whole lifetime of the program
  - We need more memory than can fit on the Stack
  - We need memory whose size is not known in advance to the caller (e.g. reading file input)

```c
// this is pseudo-C code
char* ReadFile(char* filename) {
    int size = GetFileSize(filename);
    char* buffer = AllocateMem(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 allocates it at runtime, perhaps with help from OS
  - Dynamically-allocated memory persists until either:
    - Your code explicitly deallocated 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
Aside: NULL

- **NULL** is a memory location that is **guaranteed to be invalid**
  - In C on Linux, **NULL** is 0x0 and an attempt to dereference **NULL causes a segmentation fault**

- Useful as an indicator of an uninitialized (or currently unused) pointer or allocation error
  - It’s better to cause a segfault than to allow the corruption of memory!

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

- General usage:
  
  ```c
  var = (type*) malloc(size in bytes)
  ```

- `malloc` allocates a block of memory of the requested size
  - Returns a pointer to the first byte of that memory
    - And **returns NULL** if the memory allocation failed!
  - You should assume that the memory initially contains garbage
  - You’ll typically use `sizeof` to calculate the size you need

```c
// allocate a 10-float array
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL) {
    return errcode;
}
...  // do stuff with arr
```
calloc()

- General usage:

  var = (type*) calloc (num, bytes per element)

- Like malloc, but also zeros out the block of memory
  - Helpful when zero-initialization wanted (but don’t use it to mask bugs – fix those)
  - Slightly slower; but useful for non-performance-critical code
  - malloc and calloc are found in stdlib.h

```c
// allocate a 10-double array
double* arr = (double*) calloc(10, sizeof(double));
if (arr == NULL) {
    return errcode;
}
...  // do stuff with arr
```
free()

- Usage: `free(pointer);`

Deallocates 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`)
- Freed memory becomes eligible for future allocation
- Pointer is unaffected by call to `free`
  - Defensive programming: can set pointer to `NULL` after freeing it

```c
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL)
    return errcode;
...
// do stuff with arr
free(arr);
arr = NULL; // OPTIONAL (debugging/non-performance critical code only)
```
The Heap

- The Heap is a large pool of available memory used to hold dynamically-allocated data
  - `malloc` allocates chunks of data in the Heap; `free` deallocates those chunks
  - `malloc` maintains bookkeeping data in the Heap to track allocated blocks
    - Lab 5 from 351!
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

Note: Arrow points to *next* instruction.
# Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Stack

```
nums | 1 2 3 4
ncopy
```

Heap (malloc/free)

Read/Write Segment

Read-Only Segment (main, copy)
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Stack

<table>
<thead>
<tr>
<th>nums</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ncopy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

main

<table>
<thead>
<tr>
<th>a</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Heap (malloc/free)

Read/Write Segment

Read-Only Segment (main, copy)
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Structure of the program:
- **main** function takes an array of integers and copies it to the heap.
- **copy** function is used to copy the array from the stack to the heap.
- **malloc** and **free** are used to allocate and deallocate memory on the heap.

Diagram:
- Stack: Contains the original array `nums`.
- Heap: Contains the new array `ncopy`.
- **malloc** and **free** are used to manage memory on the heap.
- The program demonstrates the use of **copy** function to copy an array from the stack to the heap.
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Stack

main

ncopy

nums | 1 | 2 | 3 | 4

Heap (malloc/free)

copy

a |

size | 4

Read/Write Segment

Read-Only Segment

(main, copy)
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Stack

```
nums: 1 2 3 4
ncopy:
```

Copy

```
a: 1 2 3 4
size: 4
i: 4
a2:
```

Heap (malloc/free)

Read/Write Segment

Read-Only Segment

(main, copy)
Heap and Stack Example

arraycopy.c

#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 argc, char** argv) {
  int nums[4] = {1, 2, 3, 4};
  int* ncopy = copy(nums, 4);
  // .. do stuff with the array ..
  free(ncopy);
  return EXIT_SUCCESS;
}
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Stack

main

Heap (malloc/free)

Read/Write Segment

Read-Only Segment

(main, copy)
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```

OS kernel [protected]

Stack

main

free

Heap (malloc/free)

Read/Write Segment

Read-Only Segment

(main, copy)
Heap and Stack Example

arraycopy.c

```c
#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 argc, char** argv) {
    int nums[4] = {1, 2, 3, 4};
    int* ncopy = copy(nums, 4);
    // .. do stuff with the array ..
    free(ncopy);
    return EXIT_SUCCESS;
}
```
Practice Question

Which line below is first guaranteed to cause an error?


A. Line 1
B. Line 4
C. Line 6
D. Line 7
E. We’re lost…

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

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

    a[2] = 5; /* write past end of array */
    b[0] += 2; /* using garbage, didn’t check for NULL */
    c = b+3; /* pointer past allocated block */
    free(&(a[0])); /* free stack address */
    free(b);
    free(b); /* freeing previously-freed address */
    b[0] = 5; /* using freed pointer */

    return EXIT_SUCCESS;
}
```
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));
    int* c;

    a[2] = 5;  // assign past the end of an array
    b[0] += 2;  // assume malloc zeros 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 freed pointer

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

memcorrupt.c
Memory Leak

- A memory leak occurs when code fails to deallocate dynamically-allocated memory that is no longer used
  - e.g. forget to `free` malloc-ed block, lose/change pointer to malloc-ed block

- What happens: program’s VM footprint will keep growing
  - This might be OK for short-lived program, since all memory is deallocated when program ends
  - Usually has bad repercussions for long-lived programs
    - Might slow down over time (e.g. lead to VM thrashing)
    - Might exhaust all available memory and crash
    - Other programs might get starved of memory
Lecture Outline

- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks

- structs and typedef
Structured Data

- **A struct** is a C datatype that contains a set of fields
  - Similar to a Java class, but with no methods or constructors
  - Useful for defining new structured types of data
  - Behave similarly to primitive variables

- **Generic declaration:**

```c
struct tagname {
    type1 name1;
    ...
    typeN nameN;
};
```

```c
// the following defines a new // structured datatype called // a "struct Point"
struct Point {
    float x, y;
};

// declare and initialize a // struct Point variable
struct Point origin = {0.0, 0.0};
```
Using structs

- Use “.” to refer to a field in a struct
- Use “->” to refer to a field from a struct pointer
  - Dereferences pointer first, then accesses field

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

int main(int argc, char** argv) {
    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; // equivalent to (*p1_ptr).y = 2.0;
    return EXIT_SUCCESS;
}
```

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
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: {%.2f,%.2f}  p2: {%.2f,%.2f}\n", p1.x, p1.y, p2.x, p2.y);
    p2 = p1;  // 0.0, 2.0  4.0, 6.0
    printf("p1: {%.2f,%.2f}  p2: {%.2f,%.2f}\n", p1.x, p1.y, p2.x, p2.y);
    return EXIT_SUCCESS;
}
```

structassign.c
typedef

- Generic format: `typedef type name;`
- Allows you to define new data type names/synonyms
  - Both `type` and `name` are usable and refer to the same type
  - Be careful with pointers – `*` before `name` is part of `type`!

```c
// make "superlong" a synonym for "unsigned long long"
typedef unsigned long long superlong;

// make "str" a synonym for "char*"
typedef char *str;

// make "Point" a synonym for "struct point_st { ... }
// make "PointPtr" a synonym for "struct point_st*"
typedef struct point_st {
    superlong x;
    superlong y;
} Point, *PointPtr; // similar syntax to "int n, *p;"

Point origin = {0, 0};
```
Dynamically-allocated Structs

- You can `malloc` and `free` structs, just like other data type
  - `sizeof` is particularly helpful here

```c
// a complex number is a + bi
typedef struct complex_st {
    double real;  // real component
    double imag;  // imaginary component
} Complex, *ComplexPtr;

// note that ComplexPtr is equivalent to Complex*
ComplexPtr AllocComplex(double real, double imag) {
    Complex* retval = (Complex*) malloc(sizeof(Complex));
    if (retval != NULL) {
        retval->real = real;
        retval->imag = imag;
    }
    return retval;
}
```
Structs as Arguments

- Structs are passed by value, like everything else in C
  - Entire struct is copied – where?
    - if too large for register, then on Stack (argument build of caller)
  - To manipulate a struct argument, pass a pointer instead

```c
typedef struct point_st {
    int x, y;
} Point, *PointPtr;

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); // prints: (  ,  )
    DoubleXWorks(&a);
    printf("(%d,%d)\n", a.x, a.y); // prints: (  ,  )
    return EXIT_SUCCESS;
}
```
Returning Structs

- Exact method of return depends on calling conventions
  - Often in %rax and %rdx for small structs
  - Often returned in memory for larger structs

```c
// a complex number is a + bi
typedef struct complex_st {
    double real; // real component
    double imag; // imaginary component
} Complex, *ComplexPtr;

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; // returns a copy of retval
}
```

complexstruct.c
Pass Copy of Struct or Pointer?

- **Value passed**: passing a pointer is cheaper and takes less space unless struct is small \((\leq \text{sizeof(\text{void*})})\)

- **Field access**: indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize \(\text{derefence = access memory}\)

- For small structs (like `struct complex_st`), passing a copy of the struct can be faster and often preferred if function only reads data; for large structs use pointers
Extra Exercise #1

- Write a program that defines:
  - A new structured type Point
    - Represent it with floats for the x and y coordinates
  - 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 and returns the area of a Rectangle
  - A function that tests whether a Point is inside of a Rectangle
Extra Exercise #2

- **Implement** `AllocSet()` and `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

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

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

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