

Systems Programming

Structs, Heap

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Relevant Course Information (1/2)

- ❖ Exercise 2 due Friday before 11 AM
 - Less leniency on submission issues compared to Exercise 1 – can use GitLab web interface to double-check (1) you pushed a tag *with the correct name* to the remote and (2) the tagged commit contains the correct submission file(s) *in the correct location*
- ❖ Section this week will involve debugging (gdb, valgrind) – bring laptop
- ❖ Meet the Staff activity due next Friday (10/16)
- ❖ HW1 due next Thursday, 10/15 @ 11:59 PM
 - You **may not** modify interfaces (.h files), but **do** read the interfaces while you're implementing them (!)
 - Suggestion: pace yourself and make steady progress

Relevant Course Information (2/2)

❖ Gitlab repo usage

- **Commit things regularly** (not all at once at the end)
 - Newly completed units of work / milestones / project parts
 - Don't push .o and executable files or other build products
- Provides backups – can retrieve old versions of files 😊
- Useful for sharing with staff members

Lecture Outline (1/2)

- ❖ **structs and typedef**
- ❖ Heap-allocated Memory
 - `malloc()` and `free()`
 - Memory leaks

Structured Data (351 Review)

❖ 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:

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

```
// 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 (351 Review)

- ❖ 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

```
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 (shallow) copies the *entire* contents!

```
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 EXIT_SUCCESS;  
}
```

structassign.c

Typedef (351 Review)

- ❖ 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!

```
// 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};
```

Check-In Activity

- ❖ Write out a C snippet that:
 - Defines a struct for a linked list node that holds (1) a character pointer and (2) a pointer to an instance of this struct
 - Typedefs the struct as `Node`

Structs as Arguments

- ❖ Structs are passed by value, like everything else in C
 - Entire struct is copied – where?
 - To manipulate a struct argument, pass a pointer instead

```
typedef struct point_st {  
    int x, y;  
} Point;  
  
void DoubleXBroken(Point p) { p.x *= 2; }  
void DoubleXWorks(Point* 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;  
}
```

structarg.c

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

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

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
- ❖ Field access: Indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize
- ❖ 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

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Which function prototype should be used?

❖ **Pop** takes the head of a linked list of **Node**, then removes and returns the first node:

_____ **Pop**(_____ head) ;

- Should the parameter be (1) **Node**, (2) **Node***, or (3) **Node****?
- Should the return type be (1) **Node** or (2) **Node***?

Lecture Outline (2/2)

- ❖ structs and typedef
- ❖ **Heap-allocated Memory**
 - **malloc()** and **free()**
 - **Memory leaks**

Why Dynamic Allocation?

- ❖ Situations where static and automatic allocation aren't sufficient:
 - We need memory that persists across multiple function calls but not for 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
 - e.g., reading file input:

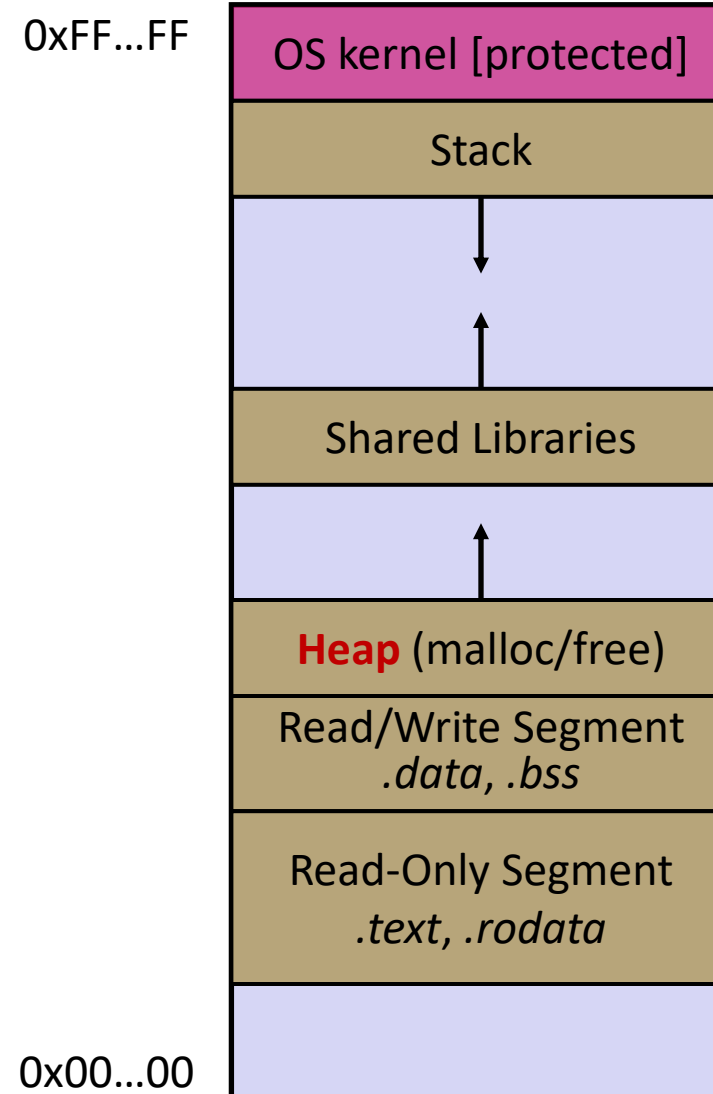
```
// this is pseudo-C code  
char* ReadFile(char* filename) {  
    int size = GetFileSize(filename);  
    char* buffer = AllocateMem(size);  
  
    ReadFileIntoBuffer(filename, buffer);  
    return buffer;  
}
```

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 deallocates it (manual/explicit memory management)
 - A garbage collector collects it (automatic/implicit memory management)
- ❖ C requires you to manually manage memory
 - Gives you more control, but causes headaches

The Heap (351 Review)

- ❖ 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!



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!

segfault.c

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



malloc()

- ❖ General usage: `var = (type*) malloc(size in bytes)`
- ❖ **malloc** allocates an uninitialized block of heap memory of at least the requested size
 - Returns a pointer to the first byte of that memory; **returns NULL** if the memory allocation failed!
 - Stylistically, you'll want to (1) use **sizeof** in your argument, (2) cast the return value, and (3) error check the return value

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

- ❖ Also, see **calloc()** and **realloc()**

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
 - Freeing `NULL` has no effect
 - The bits stored in the pointer are *not changed* by calling `free`
 - Defensive programming: can set pointer to `NULL` after freeing it

```
float* arr = (float*) malloc(10*sizeof(float));  
if (arr == NULL)  
    return errcode;  
...           // do stuff with arr  
free(arr);  
arr = NULL;   // OPTIONAL
```

Dynamically-allocated Structs

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

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

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

complexstruct.c

Heap and Stack Example (1/11)

Note: arrow points to *next* instruction to be executed.

arraycopy.c

```
#include <stdlib.h>

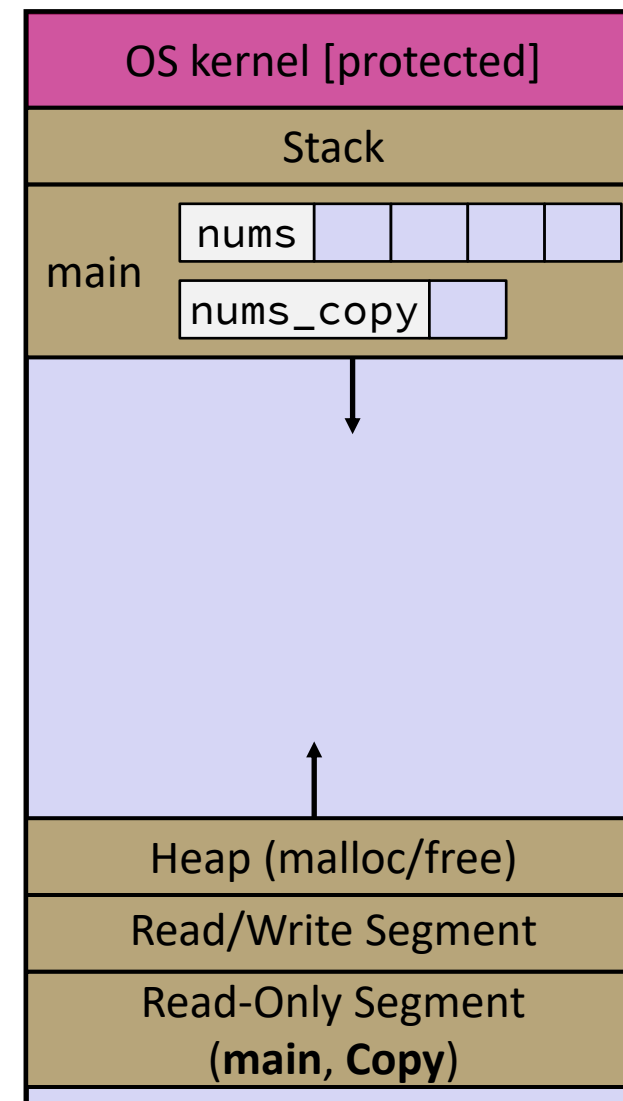
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (2/11)

arraycopy.c

```
#include <stdlib.h>

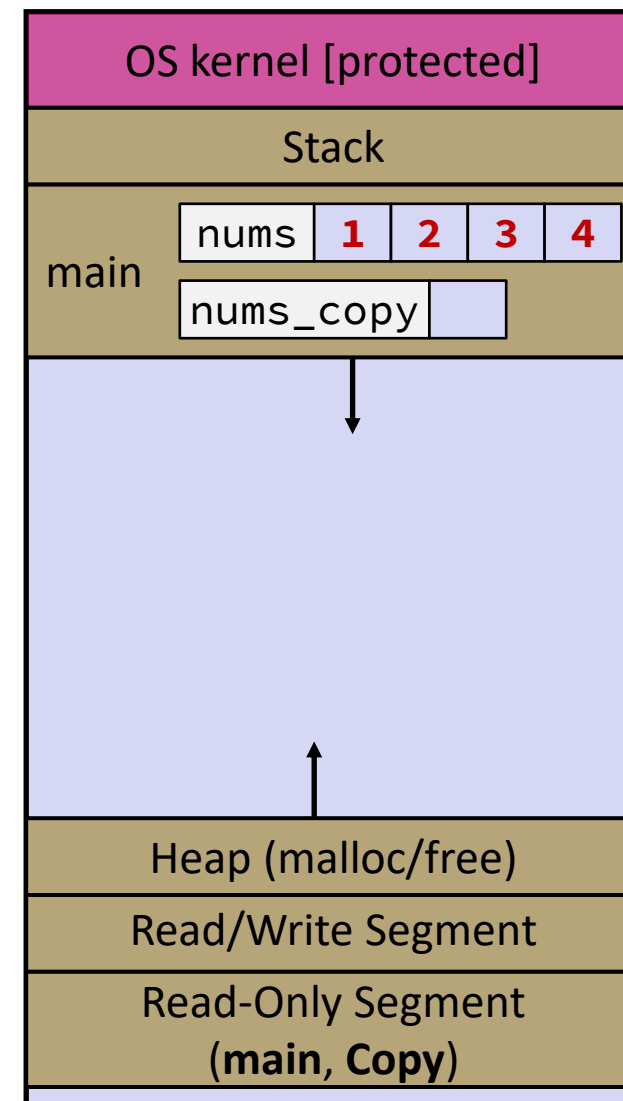
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (3/11)

arraycopy.c

```
#include <stdlib.h>

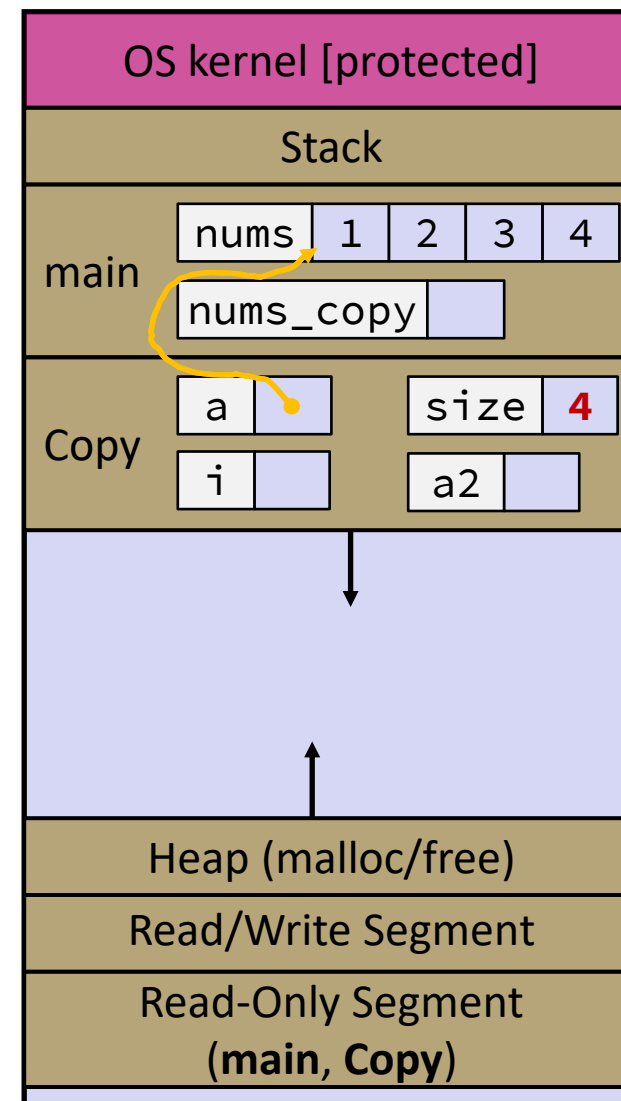
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (4/11)

arraycopy.c

```
#include <stdlib.h>

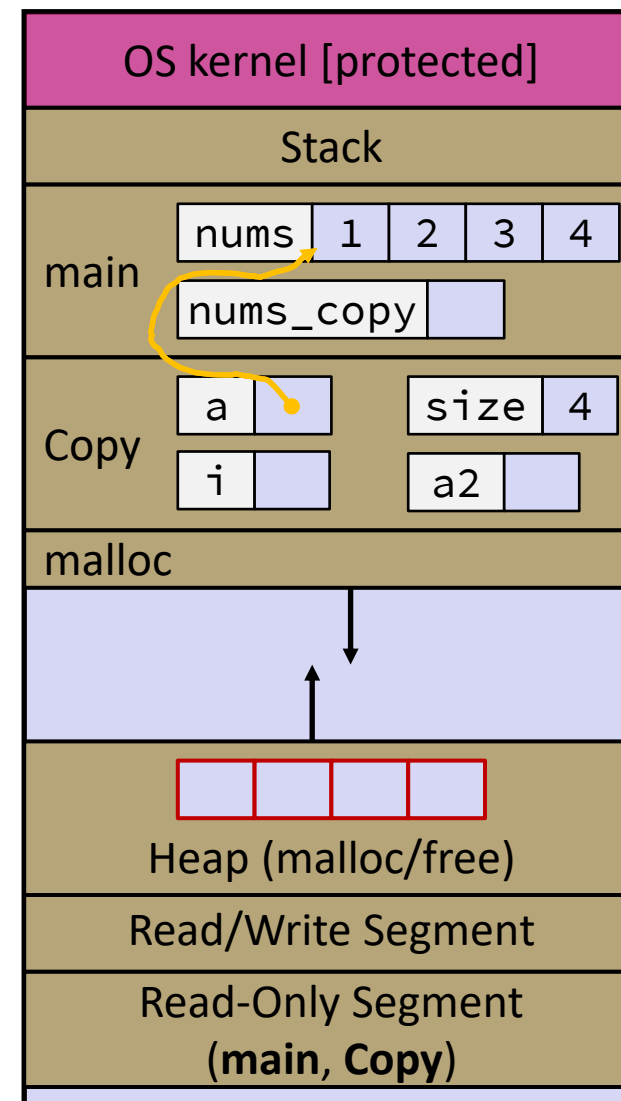
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (5/11)

arraycopy.c

```
#include <stdlib.h>

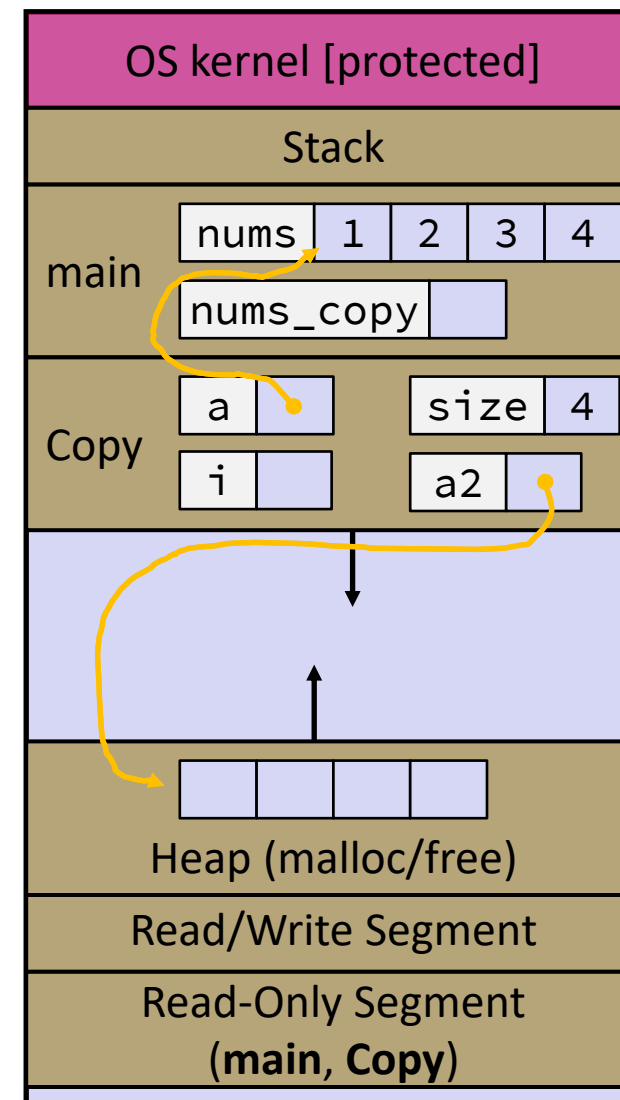
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (6/11)

arraycopy.c

```
#include <stdlib.h>

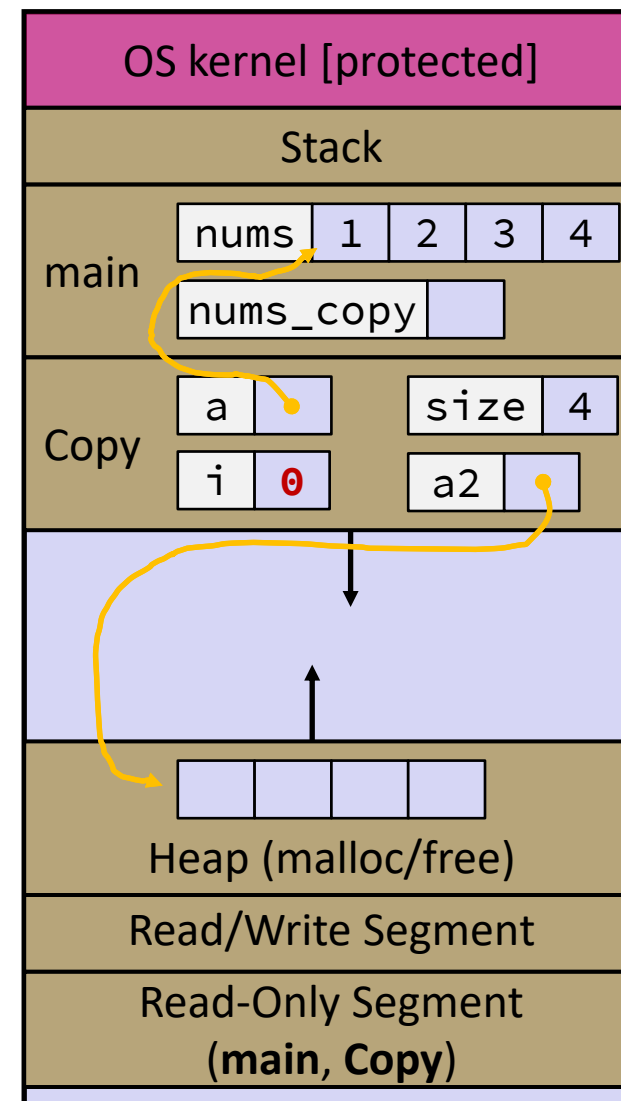
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (7/11)

arraycopy.c

```
#include <stdlib.h>

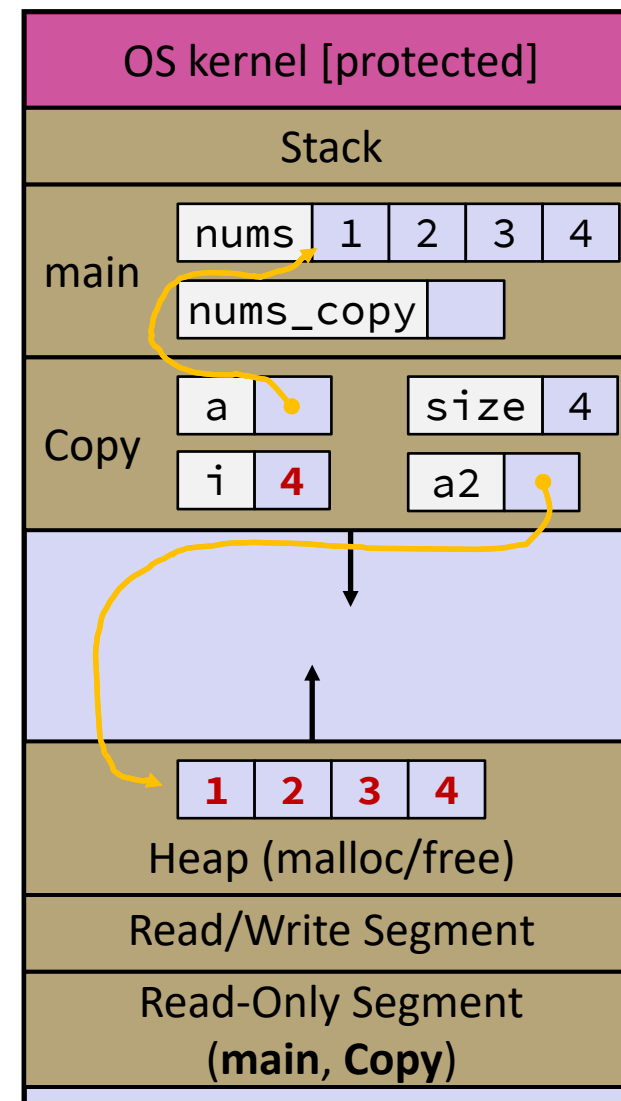
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (8/11)

arraycopy.c

```
#include <stdlib.h>

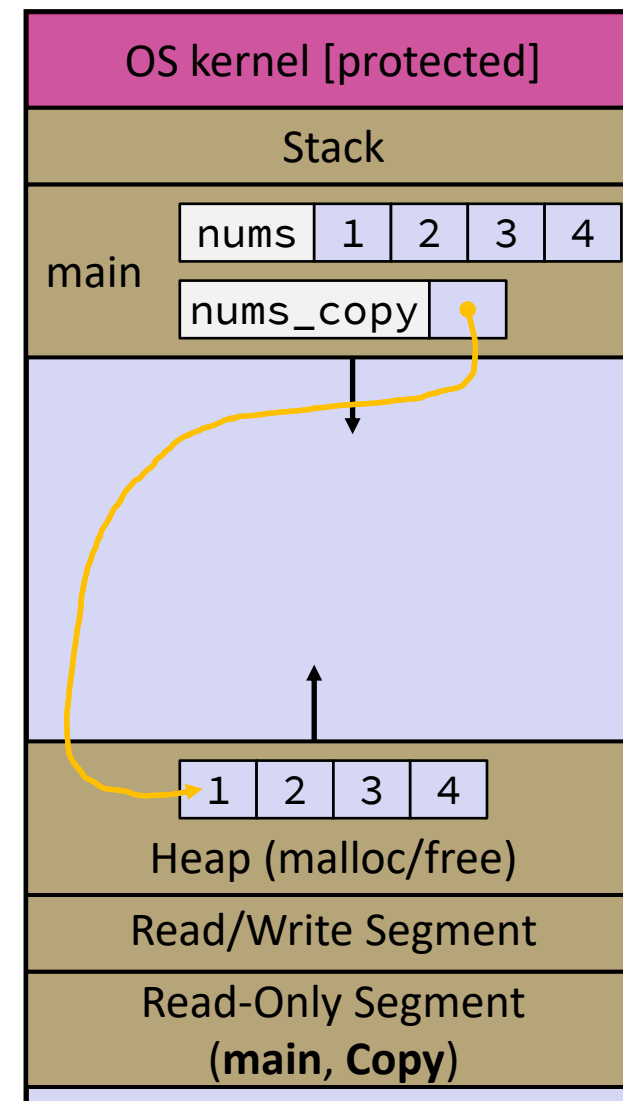
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (9/11)

arraycopy.c

```
#include <stdlib.h>

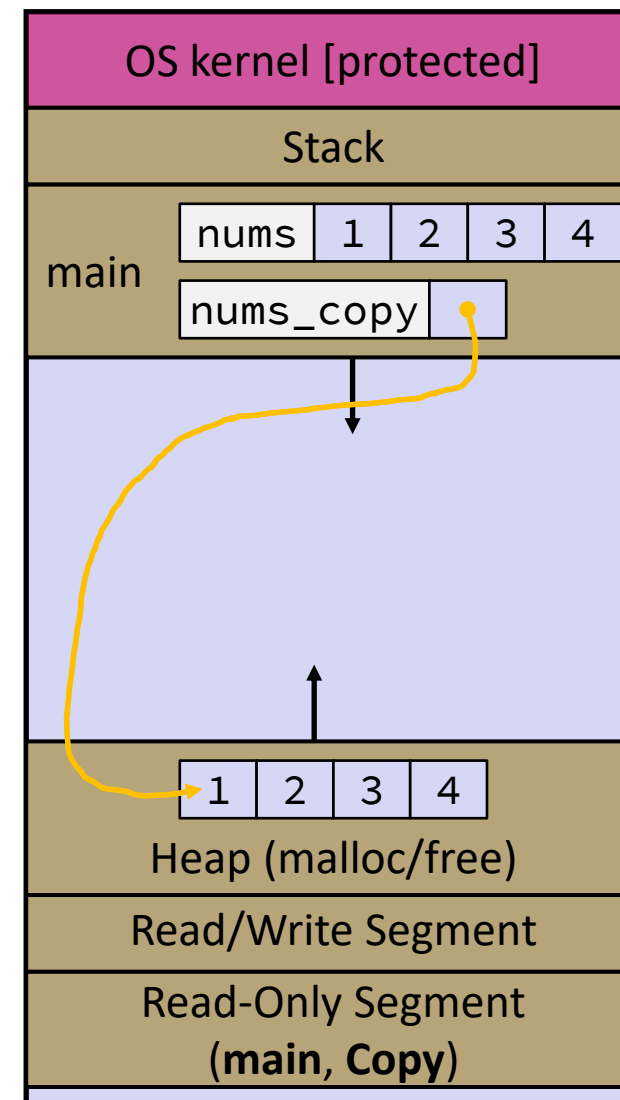
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (10/11)

arraycopy.c

```
#include <stdlib.h>

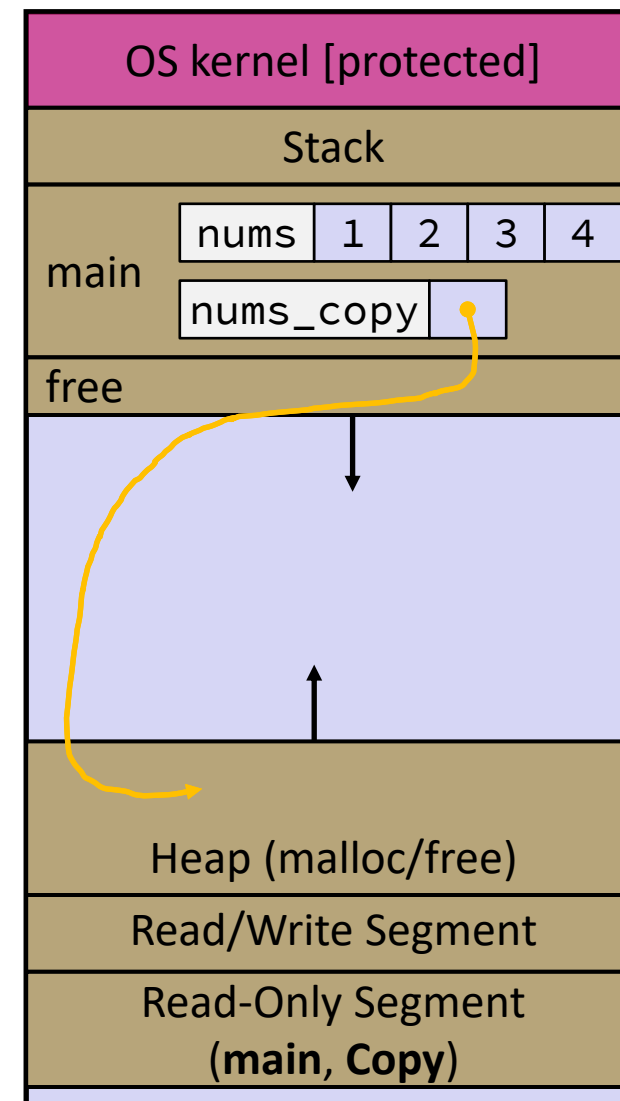
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Heap and Stack Example (11/11)

arraycopy.c

```
#include <stdlib.h>

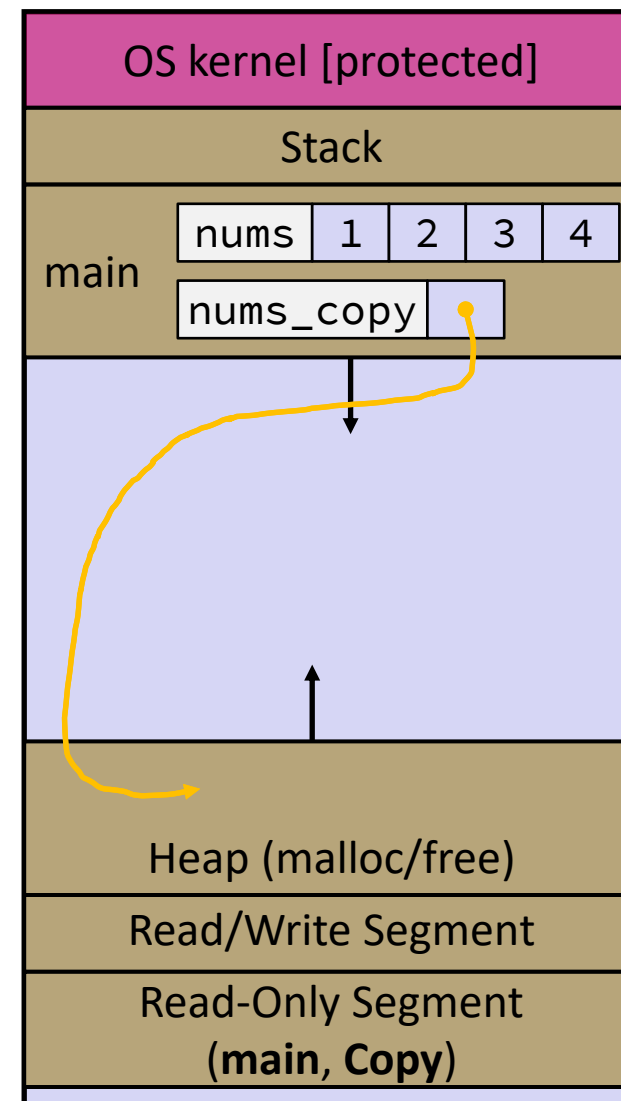
int* Copy(int a[], int size) {
    int* a2;

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

    for (int 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* nums_copy = Copy(nums, 4);
    // .. do stuff with the array ..
    free(nums_copy);
    return EXIT_SUCCESS;
}
```



Memory Leaks

- ❖ 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
 - Easier said than done; just passing pointers around – who's responsible for freeing?
- ❖ What happens: process' virtual memory footprint will keep growing
 - This might be OK for *short-lived* program, since all memory is deallocated when program ends
 - Usually has bad memory and performance repercussions for *long-lived* programs

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Which line(s) will result in undefined behavior?

- A. Line 1
- B. Line 3
- C. Line 5
- D. Line 7
- E. We're lost...

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int main(int argc, char* argv[]) {
5      int a[2];
6      int* b = malloc(2*sizeof(int));
7      int* c;
8
9      b[0] += 2;
10     c = b + 3;
11     a[2] = 5;
12     free(b);
13     free(&(a[0]));
14     free(b);
15     b[0] = 5;
16
17     return EXIT_SUCCESS;
18 }
```

memcorrupt.c

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

```
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);
```