The Heap and Structs

CSE 333 Autumn 2019

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Poll Everywhere

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About how long did Exercise 2 take?

A. 0-1 Hours
B. 1-2 Hours
C. 2-3 Hours
D. 3-4 Hours
E. 4+ Hours
F. I prefer not to say

Administrivia (1 of 2)

- 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
  - It's a good idea to master pointers quickly, because they'll be very important for the rest of the course (starting with HW 1!)

- **Exercise 3** out today and due Friday morning

Administrivia (2 of 2)

- **Homework 1** due Thursday, 10/10
  - Email Hannah if you still don't have hw1 in your repo!!!
  - You ***may not*** modify interfaces (`.h` files)
  - But ***do*** read the interfaces while you're implementing them(!)
  - Suggestion: look at `example_program_ll.c` and `example_program_ht.c` for typical usage of lists and hash tables
- GitLab repo usage
  - Commit things regularly
    - Newly completed units of work, milestones, project parts, etc.
  - Provides backup – can retrieve old versions of files ☺

Lecture Outline

- **Heap-allocated Memory**
  - **`malloc()` and `free()`**
  - **Memory leaks**
- `struct`s and `typedef`

Memory Allocation So Far

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

```
int counter = 0;      // global var

int main(int argc, char **argv) {
  counter++;
  printf("count = %d\n",counter);
  return EXIT_SUCCESS;
}
```

semantically equivalent

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

int main(int argc, char *argv[]) {
  int y = foo(10);    // local var
  printf("y = %d\n",y);
  return EXIT_SUCCESS;
}
```

- `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 or static data segments
  - We need memory whose size is not known in advance to the caller

```
// 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 deallocates it (*manual memory management*)
    - A garbage collector collects it (*automatic memory management*)

- C requires you to manually manage memory
  - Gives you more control
  - Neither better nor worse than automatic memory management if you use modern tools (eg, Valgrind) and coding conventions.

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!

what segment is 0x0 in?

segfault.c

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

malloc()

do this asap!

- General usage: `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

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

calloc()

different than malloc!

- 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

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

Aside: Memory Allocation Failures (1 of 2)

- Should we check the return value of system functions?
  - **YES**! C uses return values for letting you know about errors.
  - **BUT**! Malloc/calloc are a special case; most programs of reasonable complexity don't handle OOMs well.

- Our approach:
  - Slides and exercises (ie, simple projects) WILL check for allocation failures.
  - HWs (ie, a complex project) will NOT check for allocation failures.

Aside: Solving Allocation Failures (2 of 2)

- Shut down gracefully
  - For most complex programs, this requires allocating memory to finish database transactions, flush logfiles, etc.
  - Solution: allocated a *commited region* of memory at program start (eg, 1MB) specifically for use at shutdown. *This wastes memory in the "common case"!*
- Free some memory, then retry the allocation
  - Need to keep track of "high priority" and "low priority" regions
  - *Now malloc needs to be re-entrant!*
- *tl;dr: handling malloc failures gracefully is still unsolved*

free()

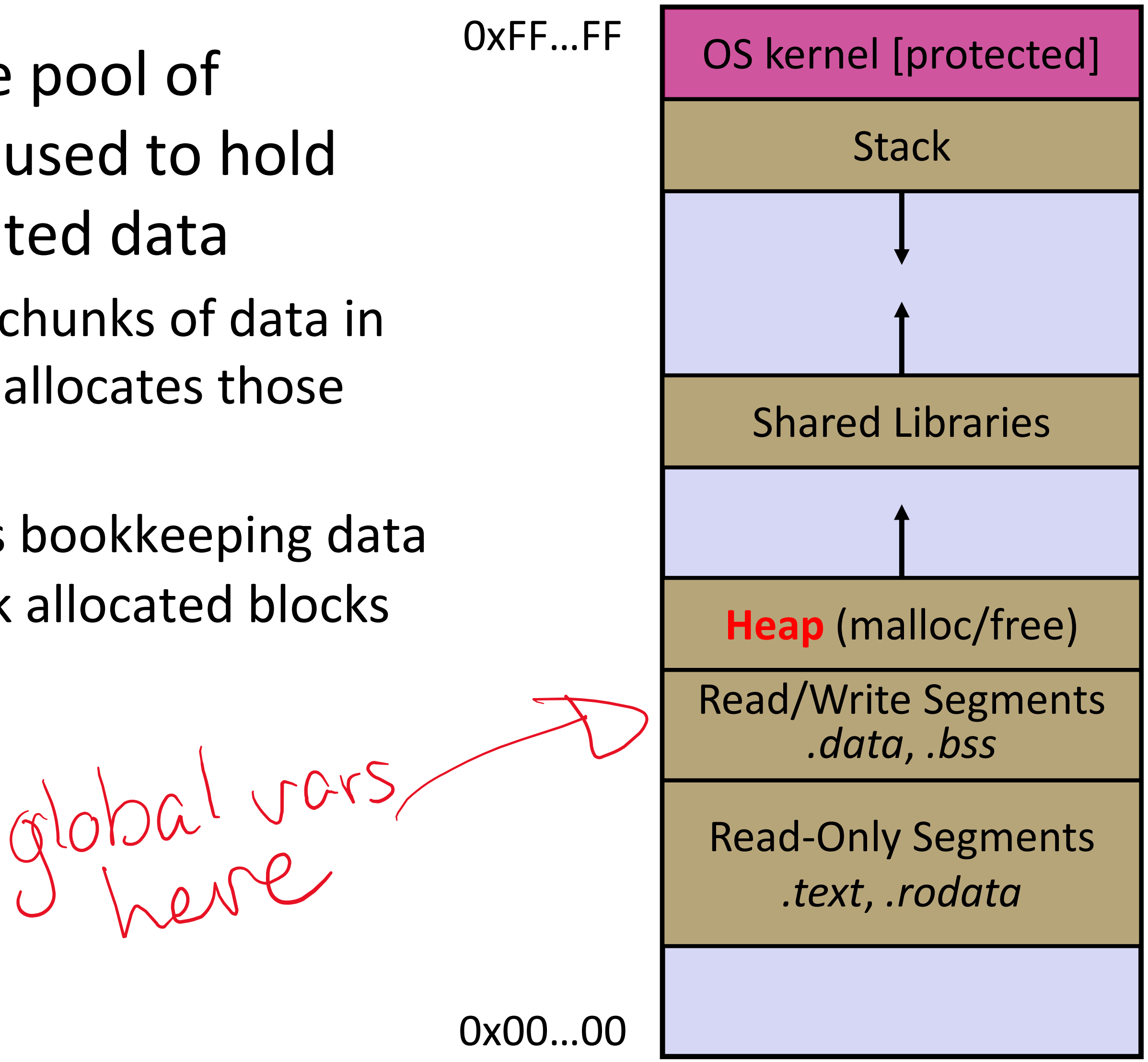
review 351 for why

- 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

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

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!

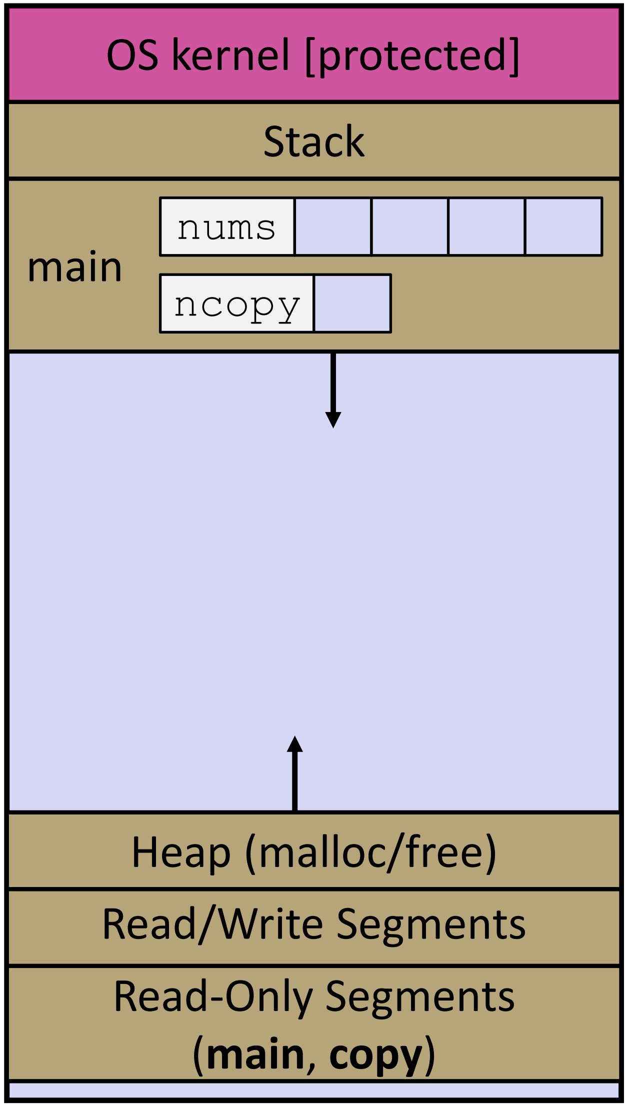


Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

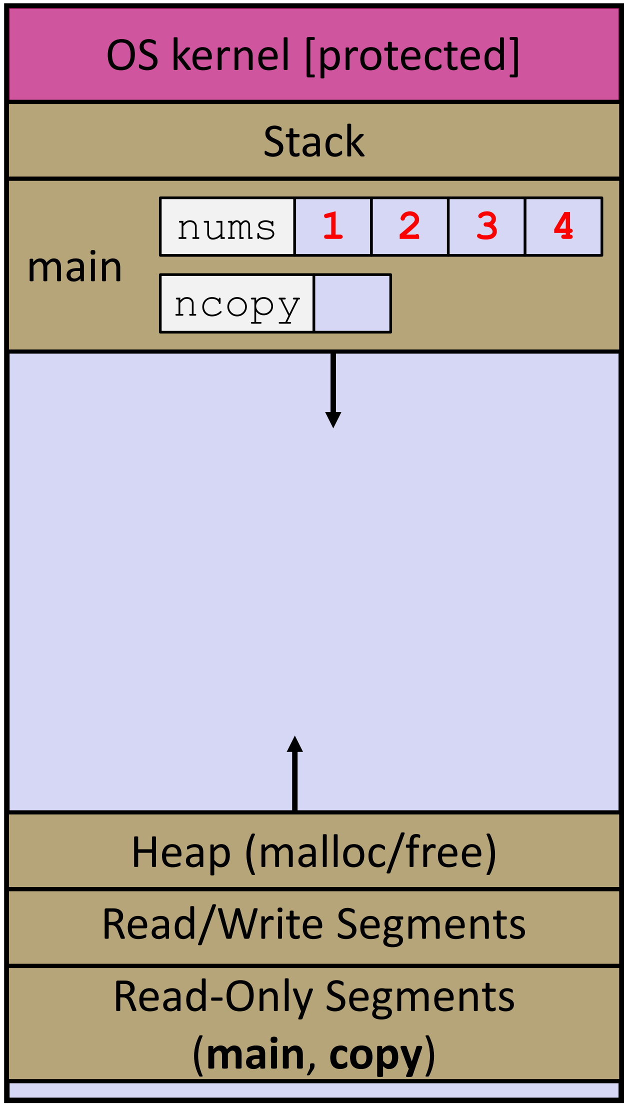
```
#include <stdlib.h>

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

  a2 = (int*) 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

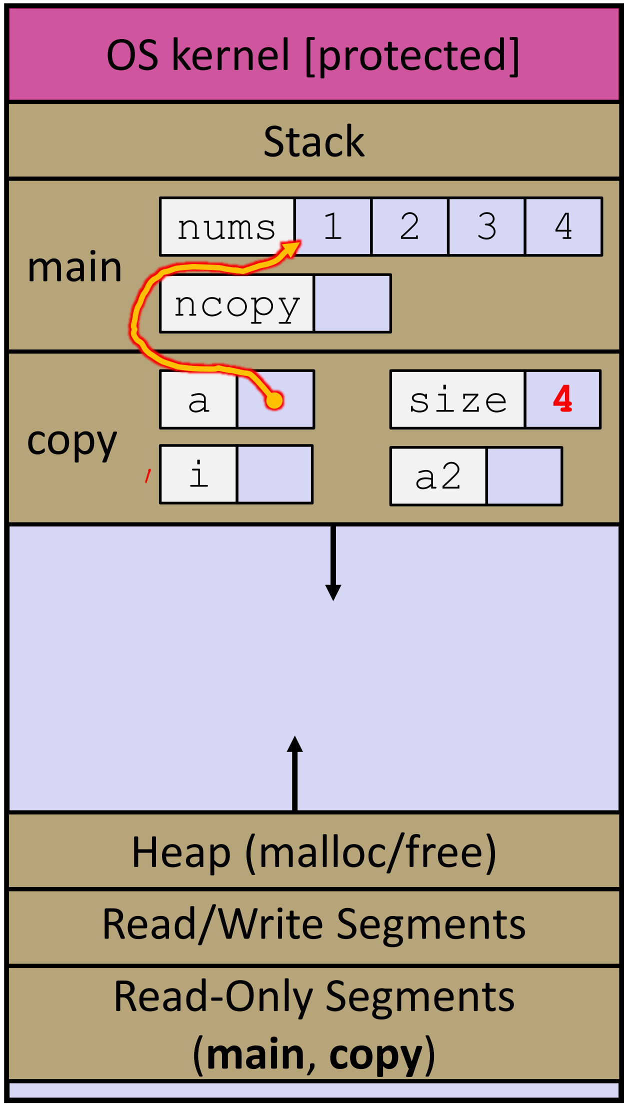
```
#include <stdlib.h>

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

  a2 = (int*) 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

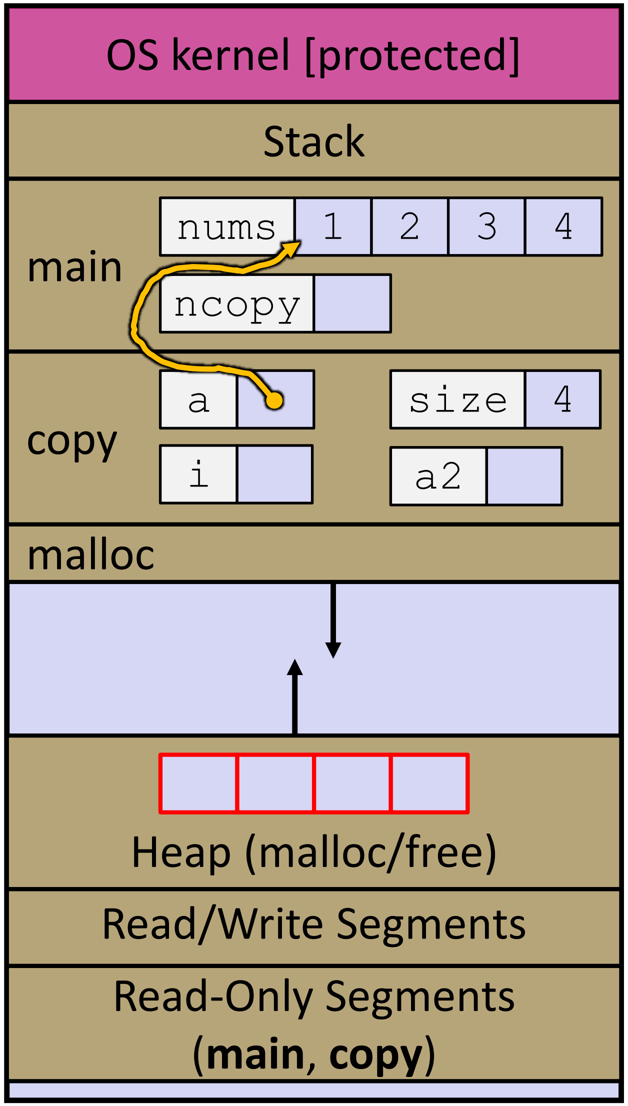
```
#include <stdlib.h>

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

  a2 = (int*) 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

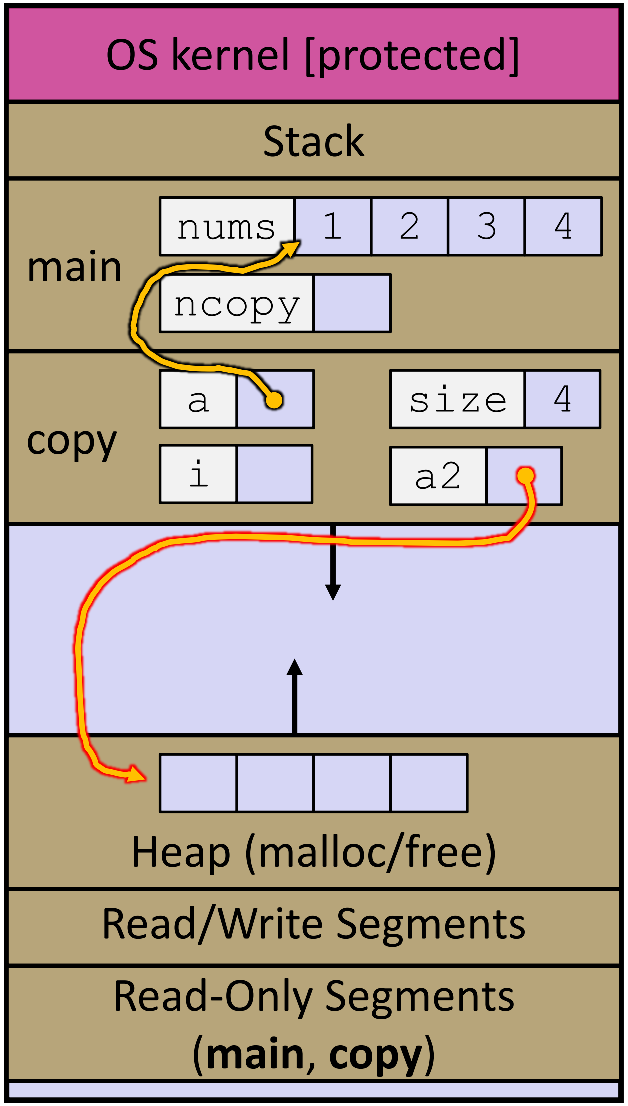
```
#include <stdlib.h>

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

  a2 = (int*) 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

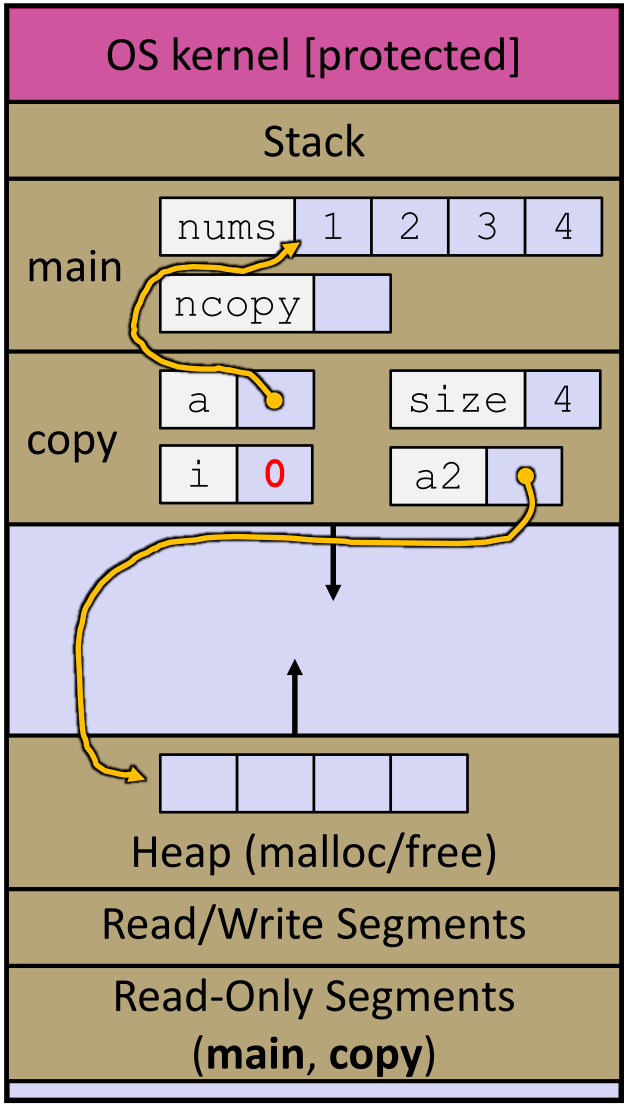
```
#include <stdlib.h>

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

  a2 = (int*) 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

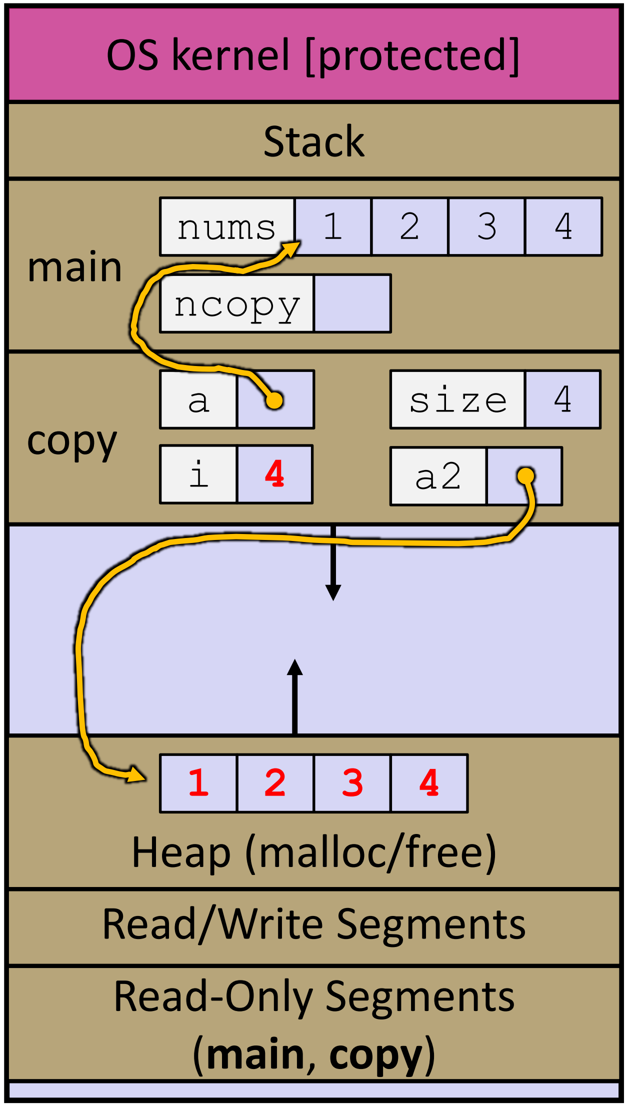
```
#include <stdlib.h>

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

  a2 = (int*) 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

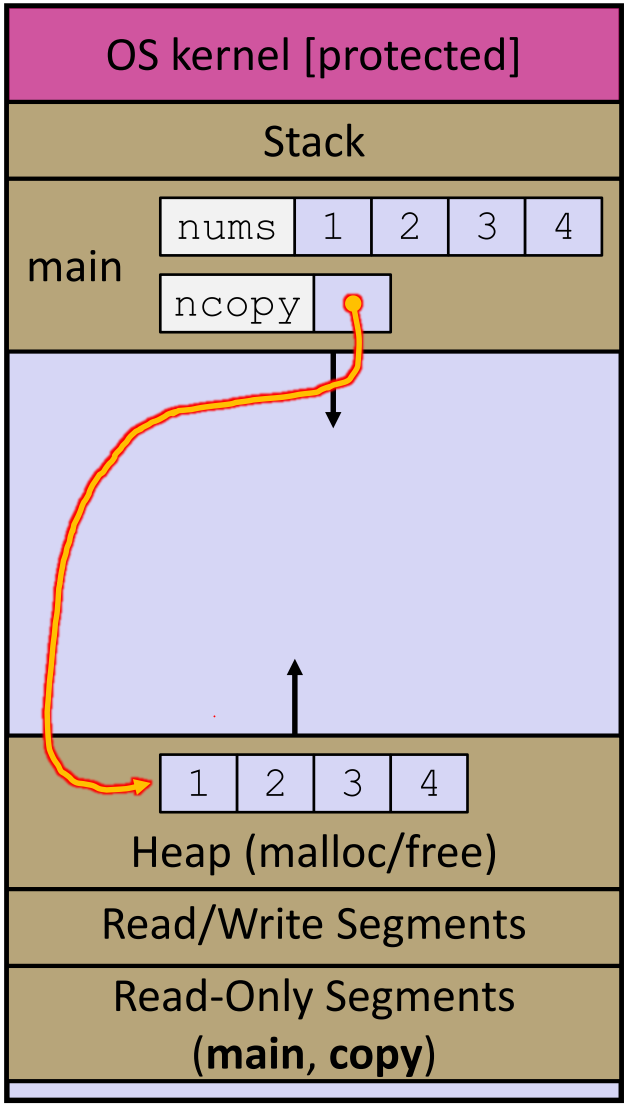
```
#include <stdlib.h>

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

  a2 = (int*) 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

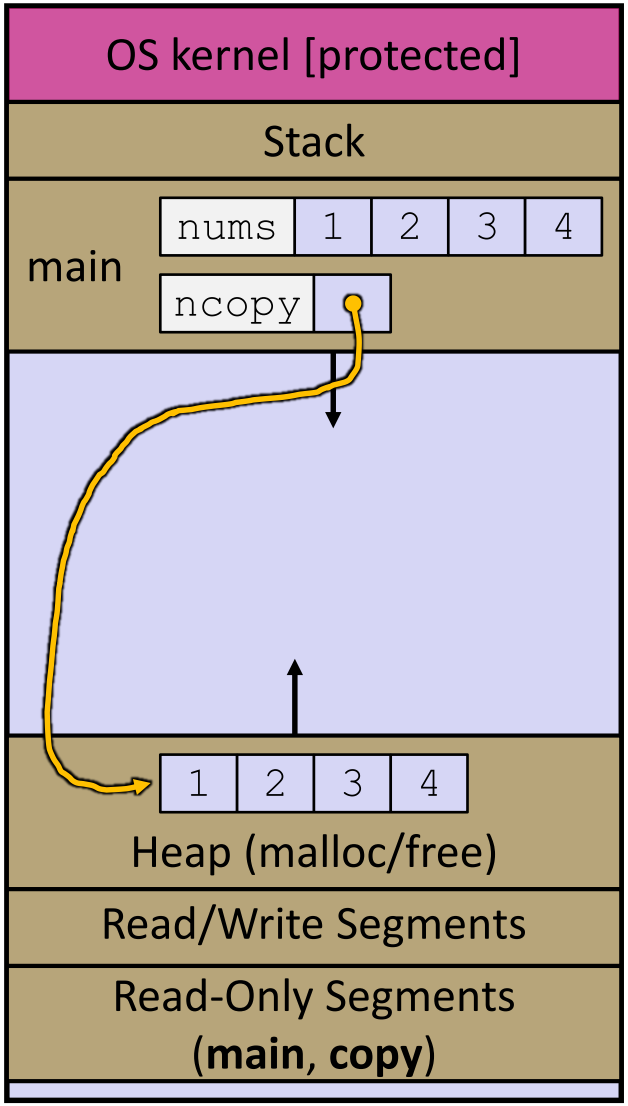
```
#include <stdlib.h>

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

  a2 = (int*) 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

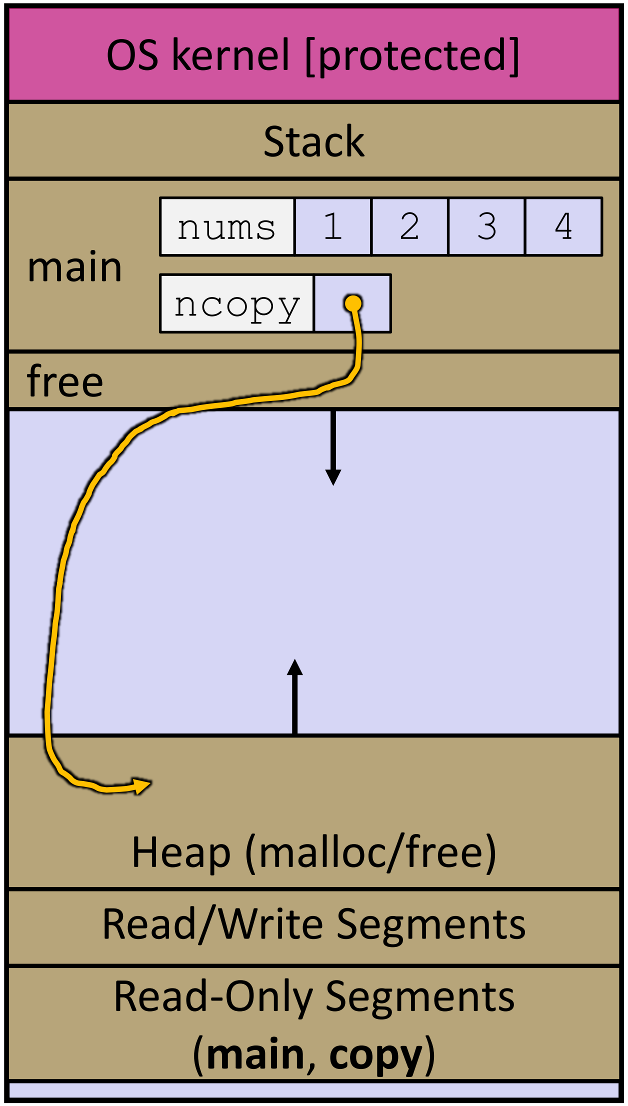
```
#include <stdlib.h>

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

  a2 = (int*) 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

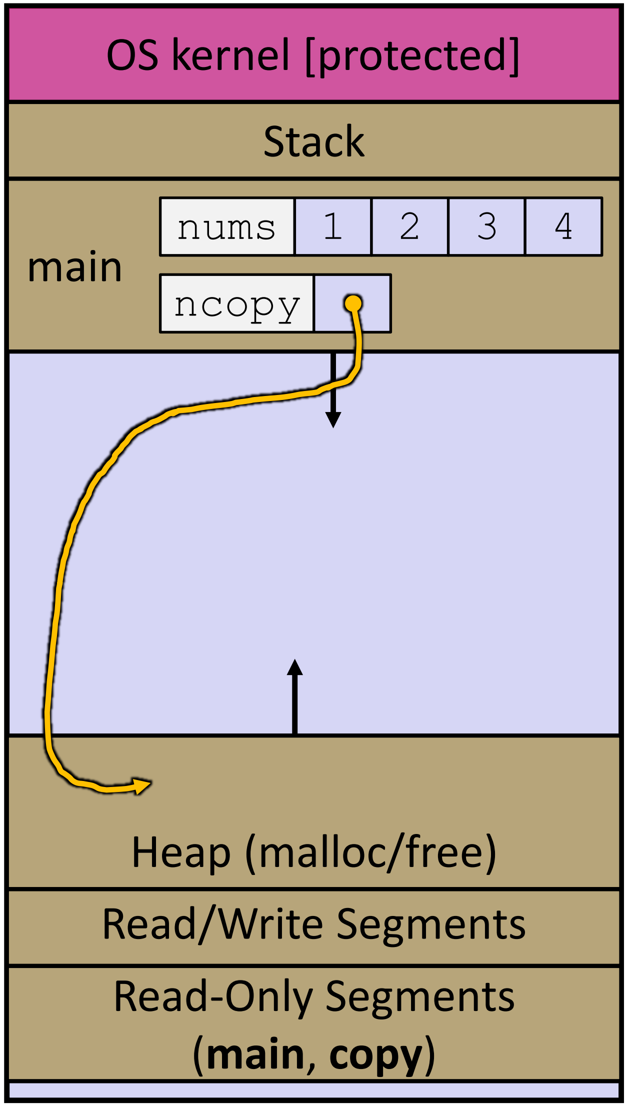
```
#include <stdlib.h>

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

  a2 = (int*) 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 = (int*) 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;
}
```



Poll Everywhere

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Which line below is first *guaranteed* to cause an error?

A. Line 1
B. Line 4
C. Line 6
D. Line 7
E. I'm not sure …

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

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

1  a[2] = 5;
2  b[0] += 2;
3  c = b+3;
4  free(&(a[0]));
5  free(b);
6  free(b);
7  b[0] = 5;

  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

  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 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 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

- Review from 351: 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};
```

can use array initialization syntax for structs too (it's fieldwise)

need "struct" as part of type

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

```
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

Structs: Assignment

- You can assign the value of a struct from a struct of the same type – *this 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

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

```
struct Point {
  int x, y;
};

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

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

int main(int argc, char **argv) {
  struct 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

- Like arguments, passed by copy
- Exact method of return depends on calling conventions
  - Often in `%rax` and `%rdx` for small structs
  - Often returned in memory for larger structs
- What about output parameters?

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

struct Complex MultiplyComplex(struct Complex x,
    struct Complex y) {
  struct 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

Structs as Arguments/Return Values: Copy vs Pointer?

- As Pointer:
  - Passing a pointer is cheaper and takes less space unless struct is small
  - Accesses through pointers are a bit more expensive and can be harder for compiler to optimize

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

Structs and Arrays

- Arrays *contained in structs* are passed by copy, just like the rest of the struct.
- … but arrays of structs are still passed by address

```
struct AlternativePoint {
  float coords[2];
};

void PrintAlternativePoint(struct AlternativePoint p) {
 printf("ap: {%f,%f} @ %p\n", p.coords[0], p.coords[1], &p.coords);
}

struct AlternativePoint ap = {{10.0, 100.0}};
printf("ap: {%f,%f} @ %p\n", ap.coords[0], ap.coords[1],
    &ap.coords);
PrintAlternativePoint(ap);
```

addresses are different
⇒ arg was copied

structsarrays.c

Dynamically-allocated Structs

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

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

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

complexstruct.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`!

```
// 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};
PointPtr originPointer = &origin;
```

Point == struct point_st

typedef can create multiple synonyms in a single statement

Extra Exercise #1

- Write a program that defines:
  - A new structured type Point
    - Represent it with `float`s 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);
```