The Heap and Structs

CSE 333

Instructor: Hannah C. Tang

Teaching Assistants:

Deeksha Vatwani	Hannah Jiang	Jen Xu
Justin Tysdal	Leanna Nguyen	Sayuj Shahi
Wei Wu	Yiqing Wang	Youssef Ben Taleb

Administrivia

- Yet another exercise, ex3, out today, due Wed morning
  - Ex0 returned; median was "Check Minus"

- HW0 grading is in flight
  - Incorrectly tagged repos are *the* largest cause of submission errors in this course!

- HW1 due a week from Tuesday
  - You should have looked through it by now
  - Be sure to read headers *carefully* while implementing
    - Header files / interfaces *may not* be changed, but ok to add local "helper" functions in .c files when appropriate
  - Pace yourself and make steady progress
    - Then you can "walk away" and come back later or the next day with a fresh look ~~if~~ when things get complicated/weird/buggy

Documentation vs Folklore…

- Documentation:
  - man pages, books
  - Reference websites: cplusplus.org, man7.org, gcc.gnu.org, etc.
- Folklore:
  - Google-ing, stackoverflow, that rando in lab or on zoom
- Tradeoffs? Relative strengths & weaknesses?
  - Discuss

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 0;
}
```

- `counter` is ***statically***-allocated
  - Allocated when program is loaded
  - Deallocated when program exits

```
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 0;
}
```

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

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
    - For example, read a file into memory....

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

  ReadFileIntoBuffer(filename, buffer);
  return buffer;
}
```

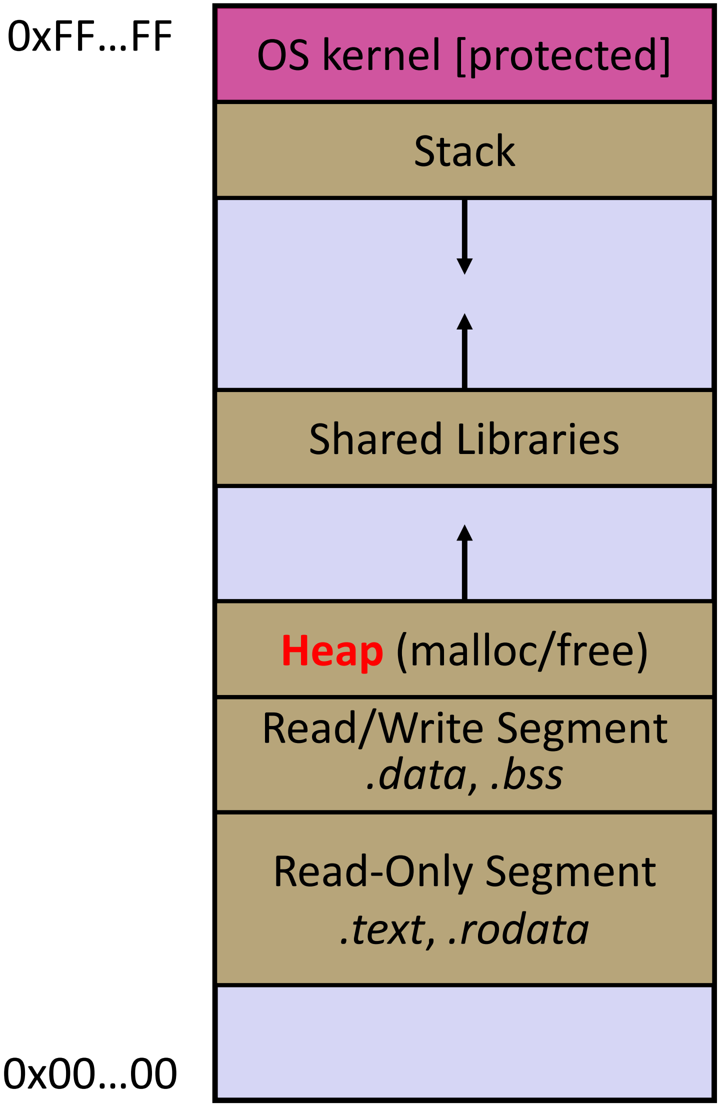
Dynamic Allocation

- What we want is ***dynamically***-allocated memory
  - Your program explicitly requests a new block of memory
    - The code 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, but causes headaches
  - Neither better nor worse than automatic memory management …
    - … if you use modern coding conventions and tools (eg, Valgrind)

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



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 0;
}
```

malloc()

- 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 and cast the result to the desired pointer type

```
// 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 or if you really are planning to zero out the new block of memory
  - **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()`

- 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 (re-)allocation
  - The bits in the pointer are *not changed* by calling free
    - Defensive programming: can set pointer to `NULL` after freeing it

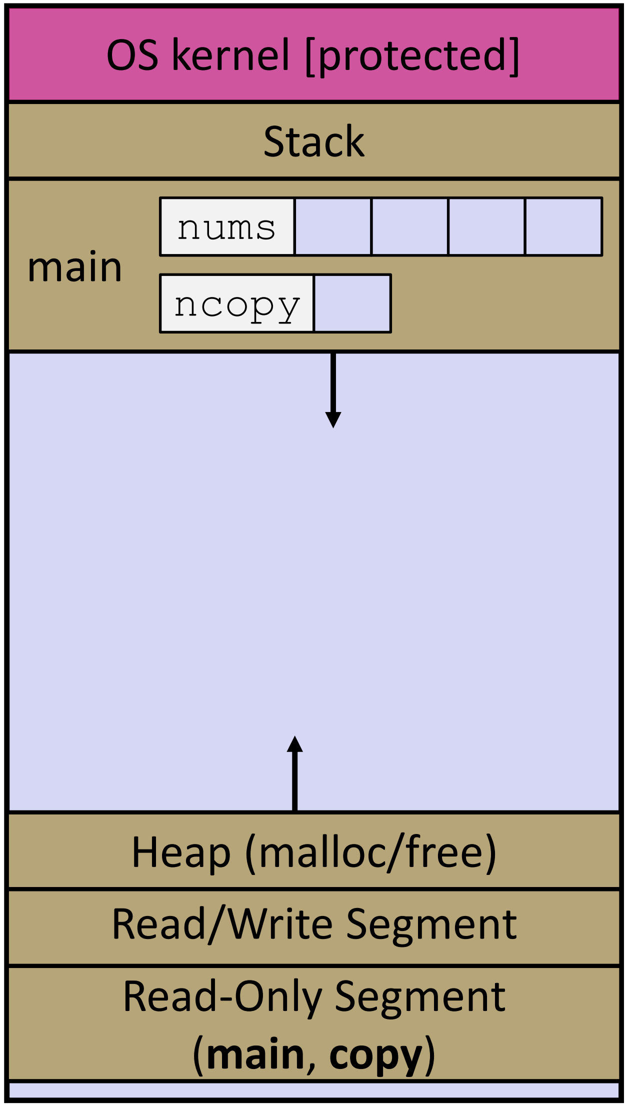
```
float* arr = (float*) malloc(10*sizeof(float));
if (arr == NULL)
  return errcode;
...              // do stuff with arr
free(arr);
arr = NULL;      // OPTIONAL
```

Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

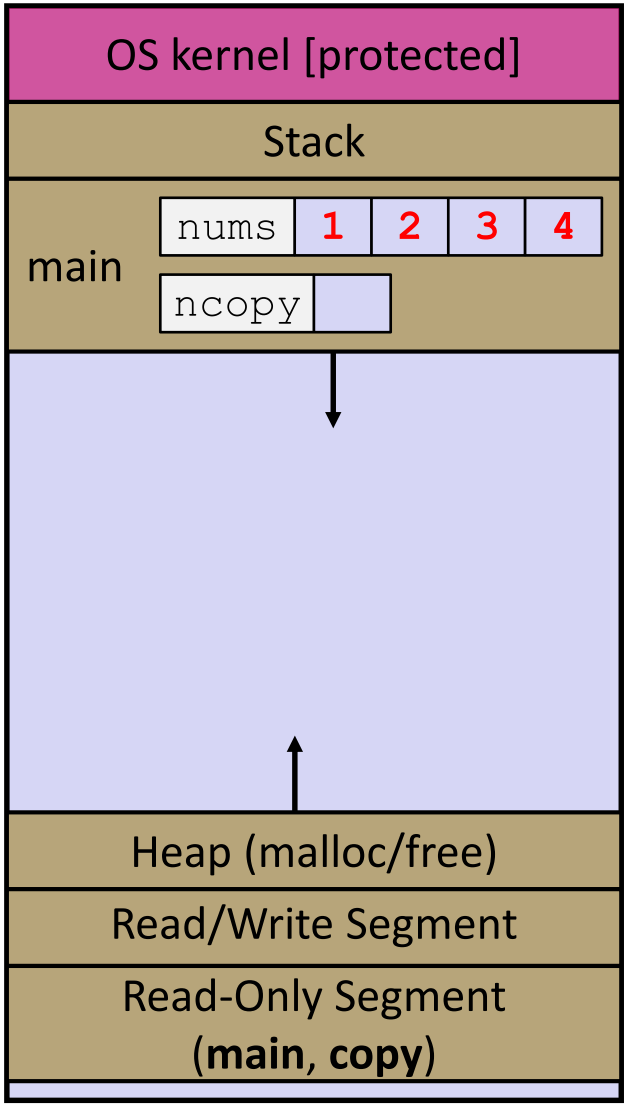
```
#include <stdlib.h>

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

  a2 = 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 0;
}
```



Heap and Stack Example

arraycopy.c

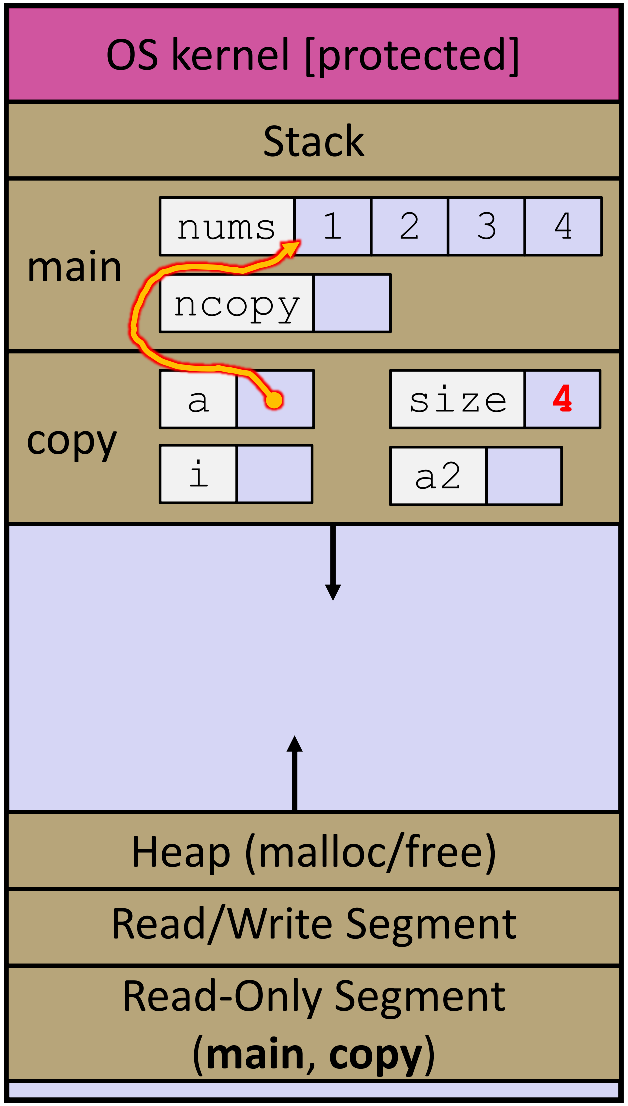
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

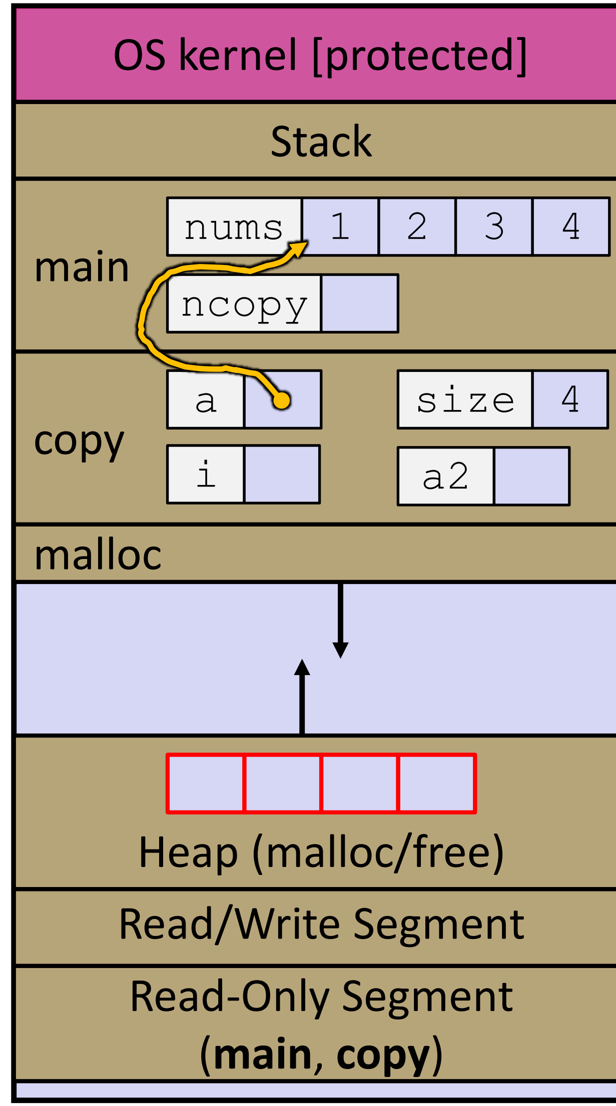
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

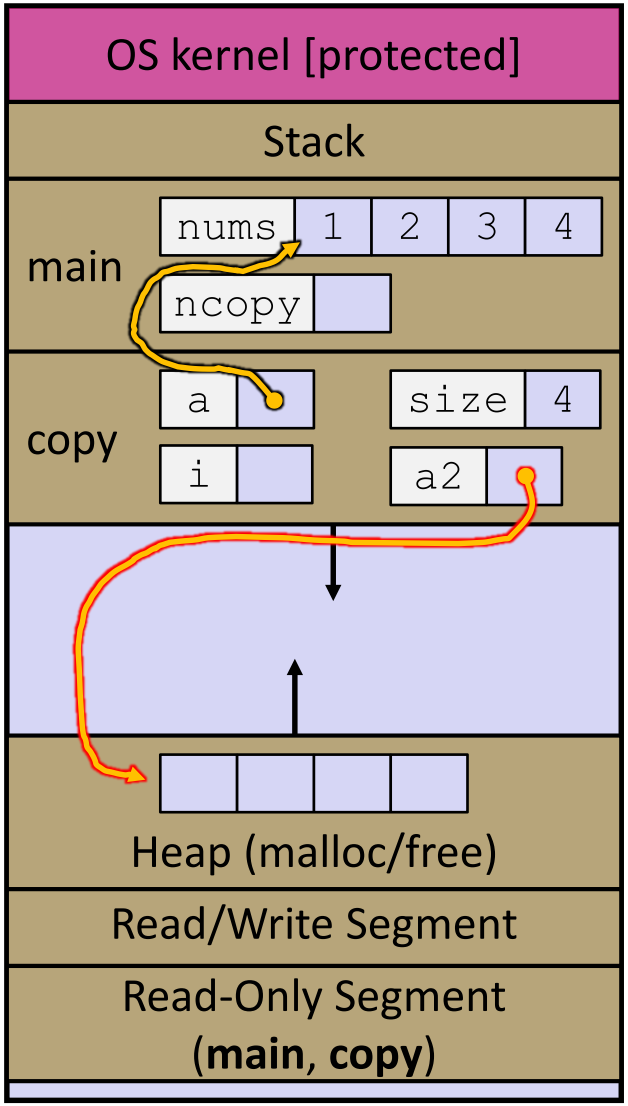
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

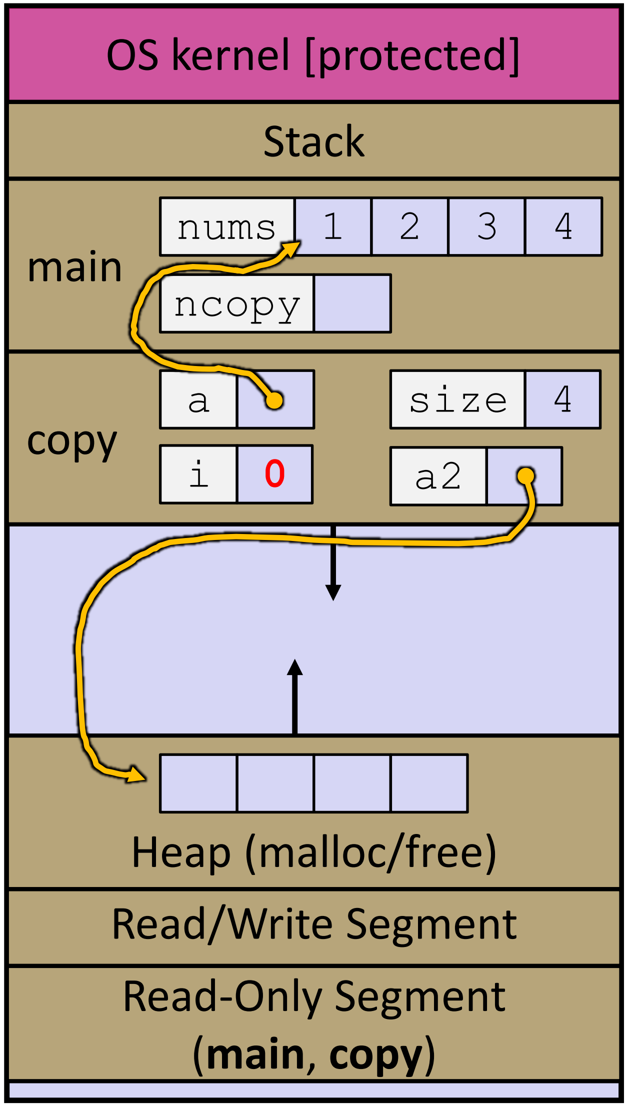
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

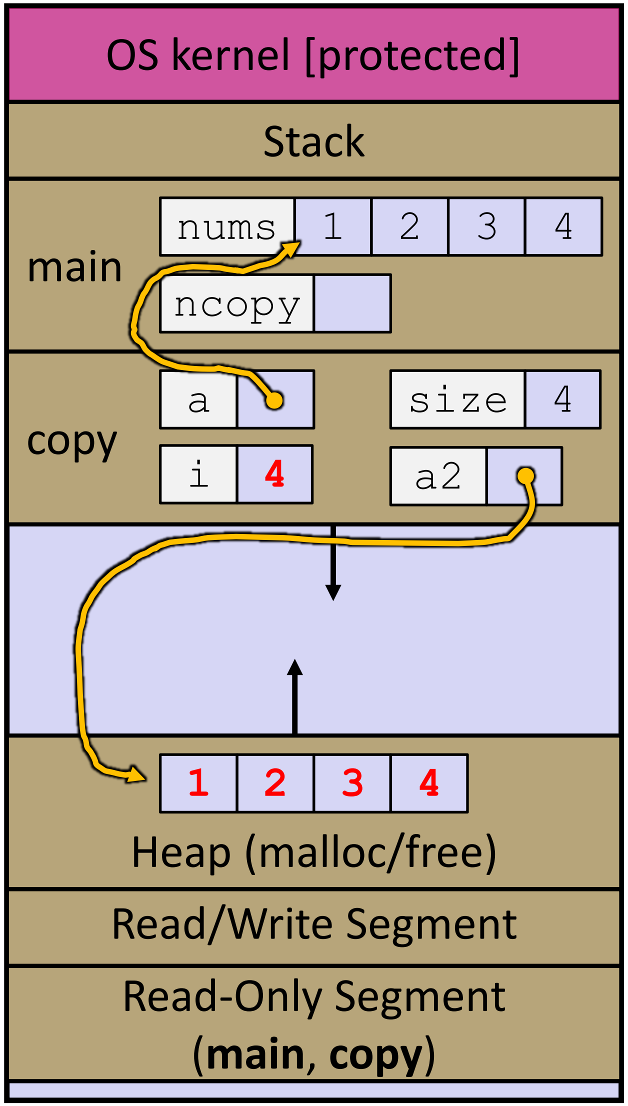
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

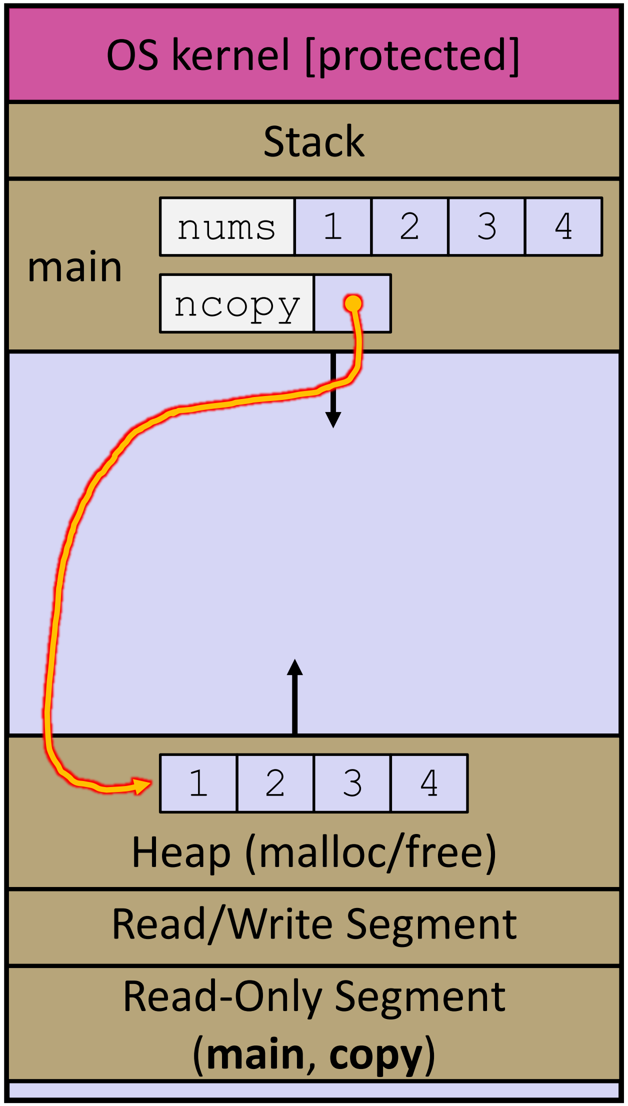
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

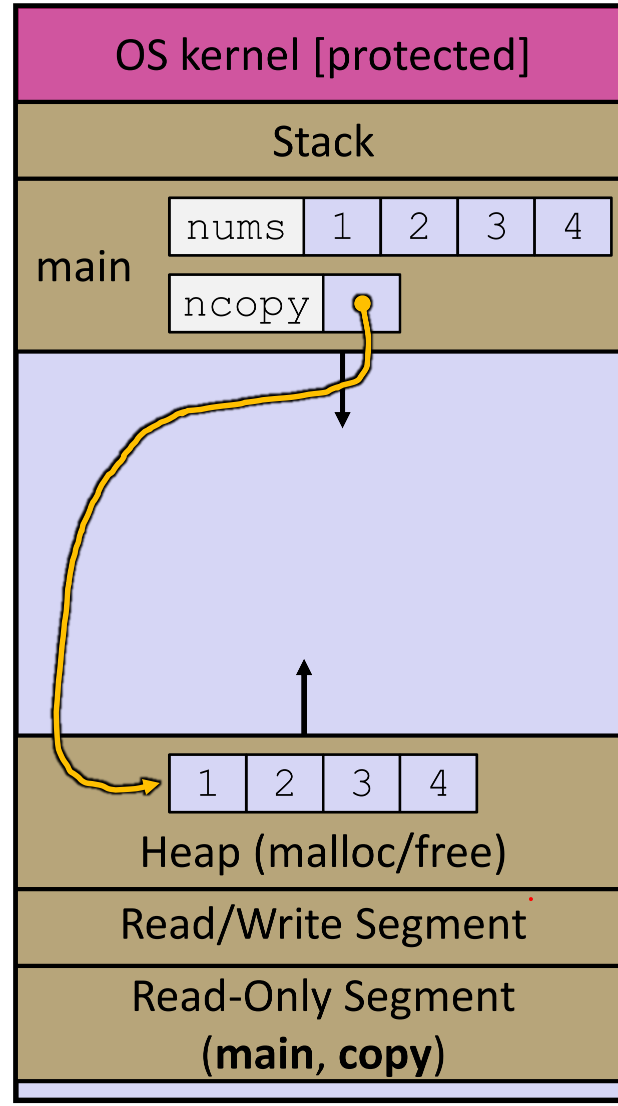
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

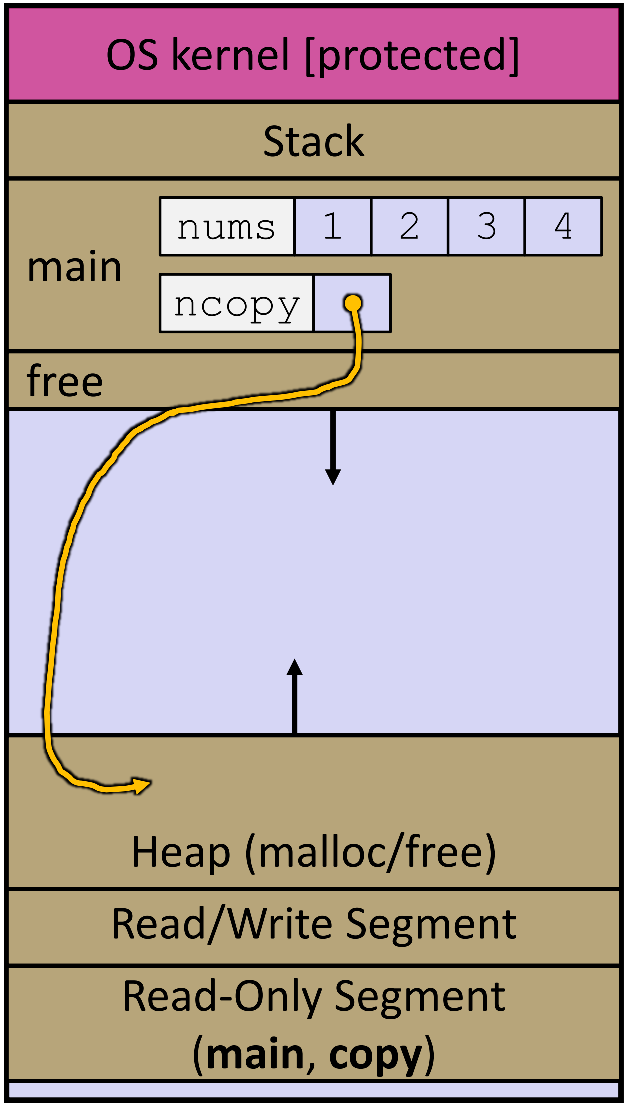
```
#include <stdlib.h>

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 0;
}
```



Heap and Stack Example

arraycopy.c

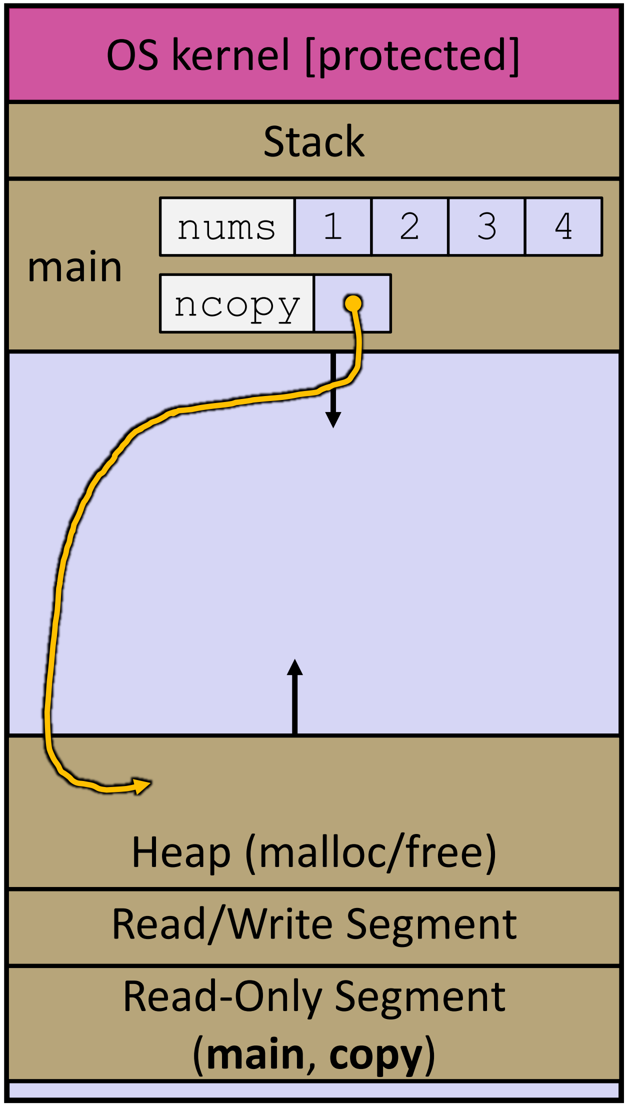
```
#include <stdlib.h>

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 0;
}
```



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 0;
}
```



Poll Everywhere pollev.com/uwcse333

- Choose one of the numbered lines and explain to a neighbor why it is a bug

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

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

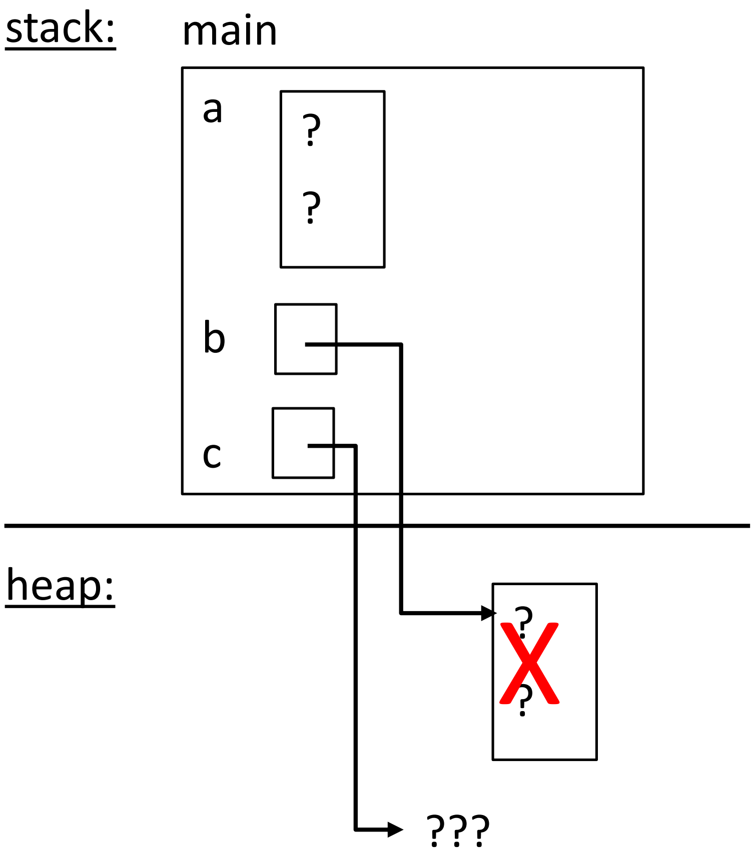
Memory Corruption

- There are all sorts of ways to corrupt memory in 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 (dangling) pointer

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

memcorrupt.c

Memory Corruption - What Happens?




```
#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 (dangling) pointer

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

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 the block
  - Takes real work to prevent – as pointers are passed around, what part of the program is responsible for freeing each 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
  - Act similarly to primitive variables (can assign, pass by value, …)
  - A struct *tagname* is a *tag*; ***not*** a full first-class type name
- 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

- Use " . " to refer to a field in a struct
- Use "->" to refer to a field from a struct pointer
  - Shorthand for: dereference pointer first, then accesses field
    - Using p->x instead of (*p).x is standard practice – do it that way

```
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 0;
}
```

simplestruct.c

Which Copy?

- We've seen values being copied (primitive types)

```
int main(int argc, char** argv) {
  int x = 123;
  int y = x;

  return 0;
```

- We've seen addresses being copied (arrays)

```
int main(int argc, char** argv) {
  int x[] = {1, 2, 3};
  int y[] = x;

  return 0;
```

- Which one happens when we copy a struct instance?

Copy by Assignment

- You can assign the value of a struct from a struct of the same type – *this copies the entire contents byte-for-byte!*

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

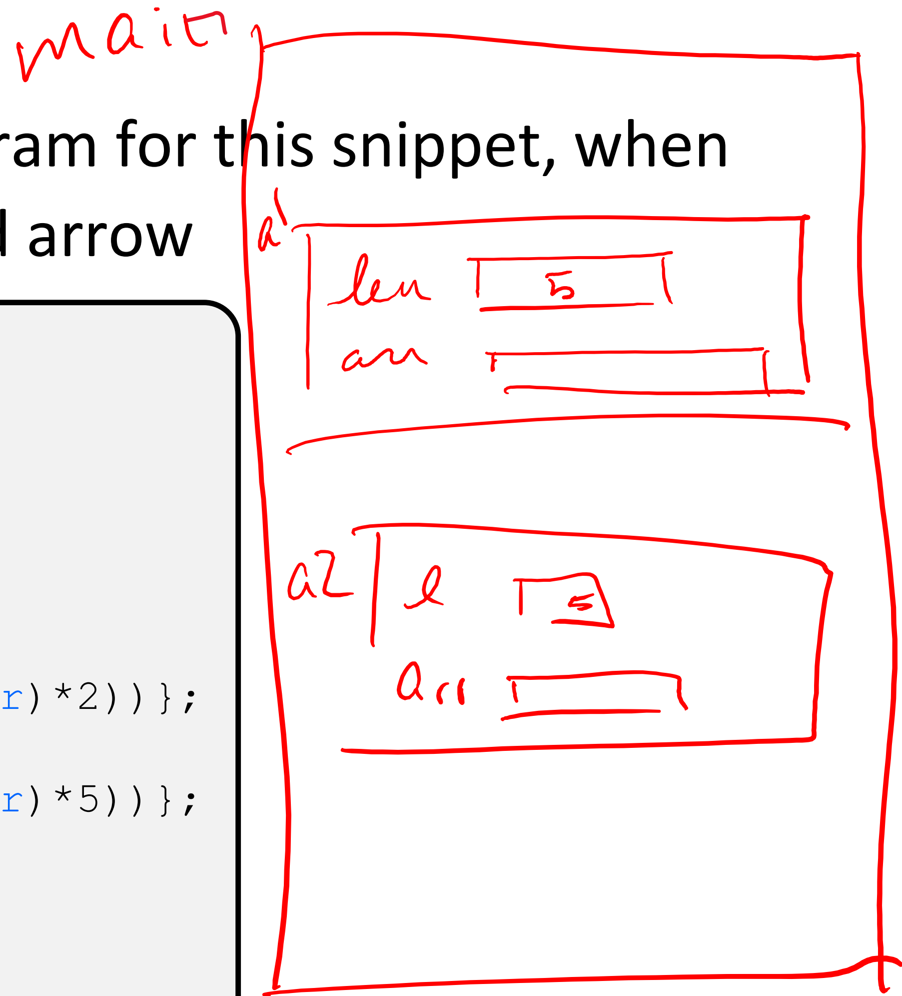
structassign.c

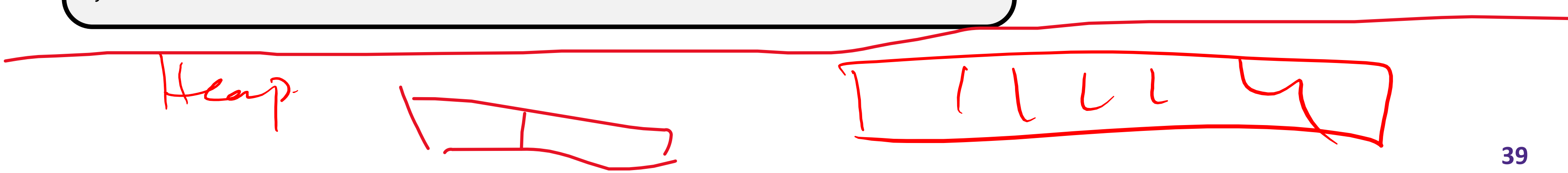
Poll Everywhere

pollev.com/uwcse333

- Draw the box-and-arrow diagram for this snippet, when execution has reached the red arrow

```
struct SmartArray {
  int len;
  char* arr;
};

int main(int argc, char** argv) {
  struct SmartArray a1
    = {2, (char*)malloc(sizeof(char)*2)};
  struct SmartArray a2
    = {5, (char*)malloc(sizeof(char)*5)};
  a1 = a2;

→ return 0;
}
```





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 0;
}
```

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};
```

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, *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;
}
```

complexstruct.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, *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

Passing Structs: Copy or Pointer?

- Cost of Copies: if the struct is smaller than a pointer type, passing by copy is cheaper

- Cost of Accesses: accesses through pointers require more "jumping around memory"; more expensive and can be harder for compiler to optimize

- Decision:
  - For small structs (like `struct complex_st`), passing a copy of the struct can be faster and often preferred if function only reads data
  - or large structs or if the function should change caller's data, 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);
```

structsarrays.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);
```