Poll Everywhere

pollev.com/cse333

What is your anticipated lecture/section attendance modality (for the time being)?

A. In person until the University dictates otherwise

B. In person with some hesitation

C. Remote, synchronously

D. Remote, asynchronously

The Heap and Structs

CSE 333 Winter 2022

Instructor: Justin Hsia

Teaching Assistants:

Aakash Srazali	Assaf Vayner	Brenden Page
Cleo Chen	Dan Constantinescu	Dylan Hartono
Elizabeth Haker	Jacob Christy	Julia Wang
Kenzie Mihardja	Kyrie Dowling	Mengqi Chen
Mitchell Levy	Timmy Yang	

Relevant Course Information (1/2)

- Exercise grades
  - We will be giving "autograder correction" points
  - Regrade requests: open 24 hr after, close 72 hr after release
- hw0 due tonight *before* 11:59 pm (and 0 seconds)
  - 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, 1/20 @ 11:59 pm
  - You ***may not*** modify interfaces (`.h` files), but ***do*** read the interfaces while you're implementing them (!)
  - Record bugs in `bugjournal.md`
  - 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 and partner

Lecture Outline

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

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;
}
```

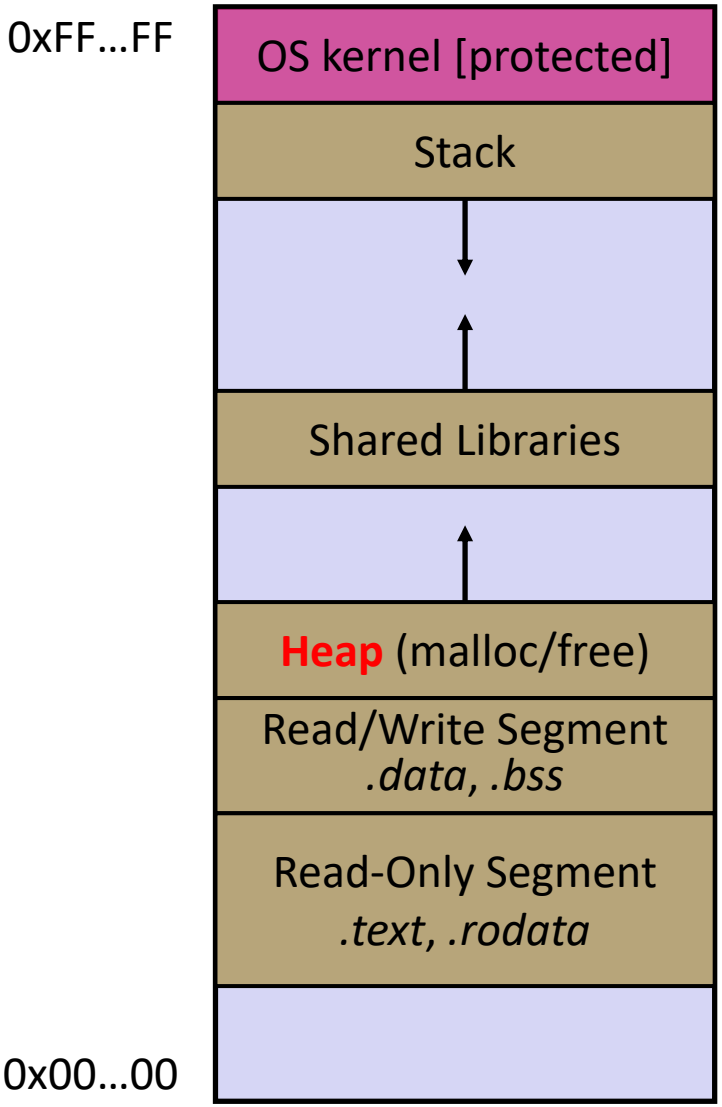
Dynamic Allocation

- 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
```

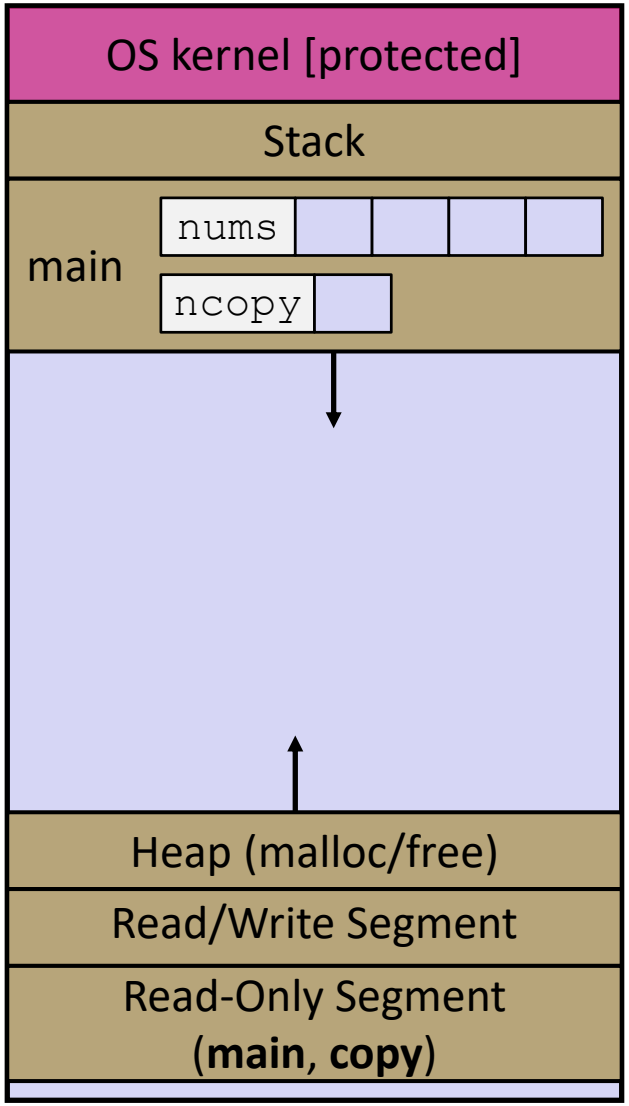
(debugging/non-performance critical code only)

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));   // should be (int*) here
  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;
}
```

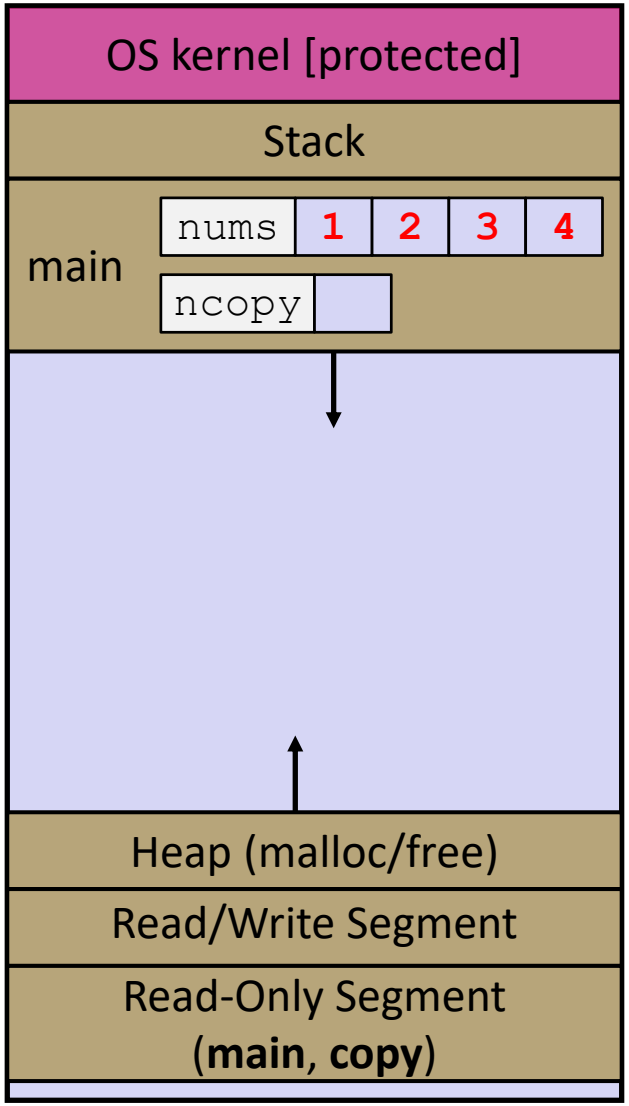


Heap and Stack Example

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 EXIT_SUCCESS;
}
```

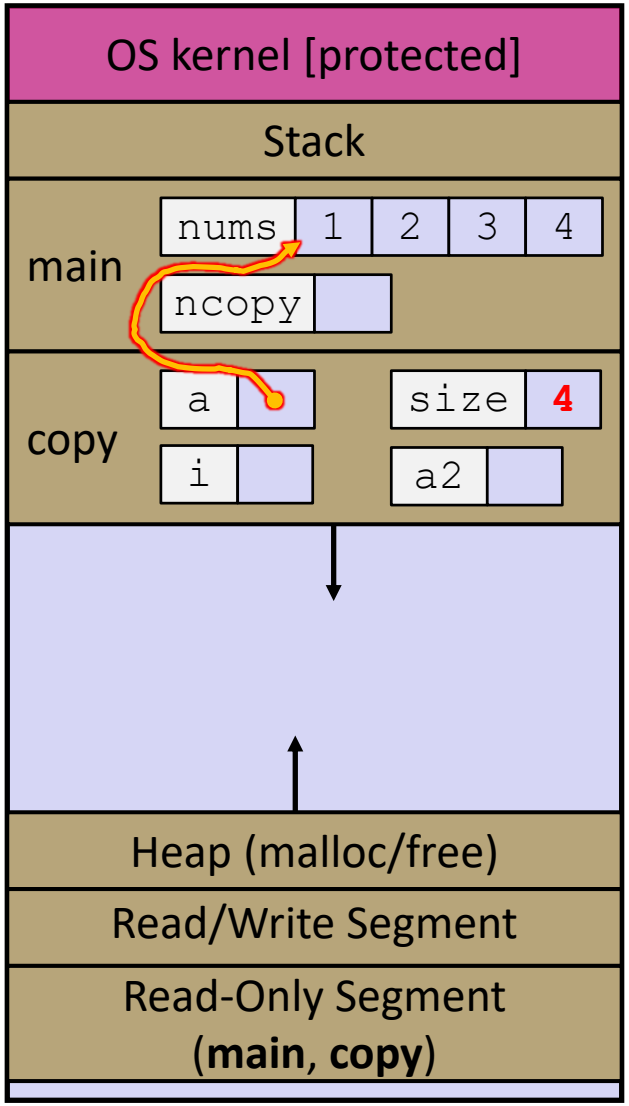


Heap and Stack Example

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 EXIT_SUCCESS;
}
```

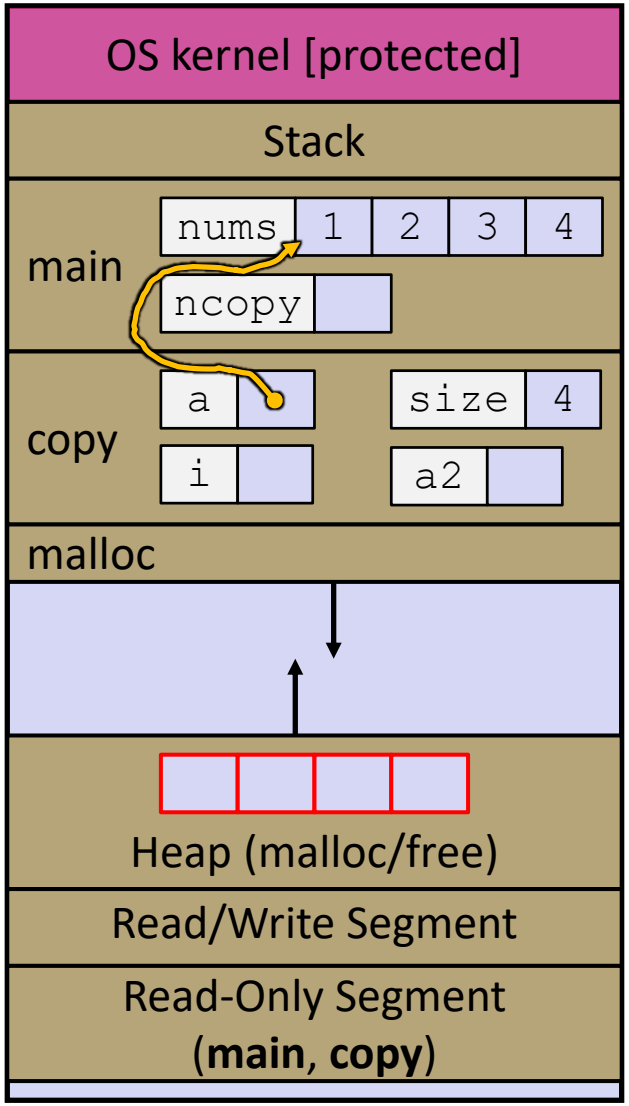


Heap and Stack Example

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 EXIT_SUCCESS;
}
```



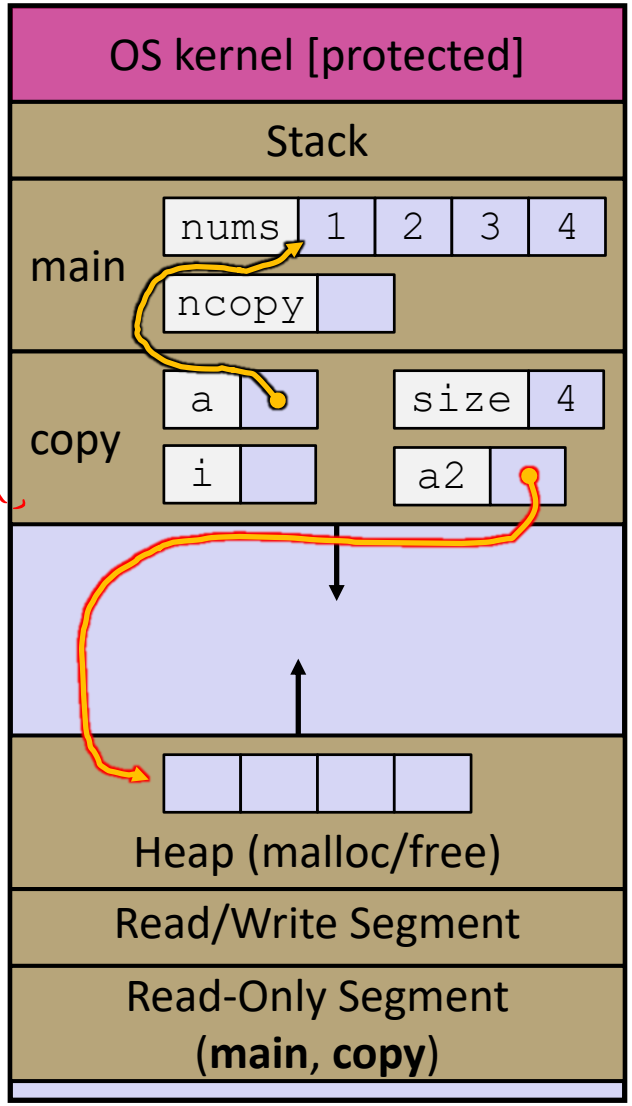
Heap and Stack Example

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 EXIT_SUCCESS;
}
```

if succeeded, otherwise NULL

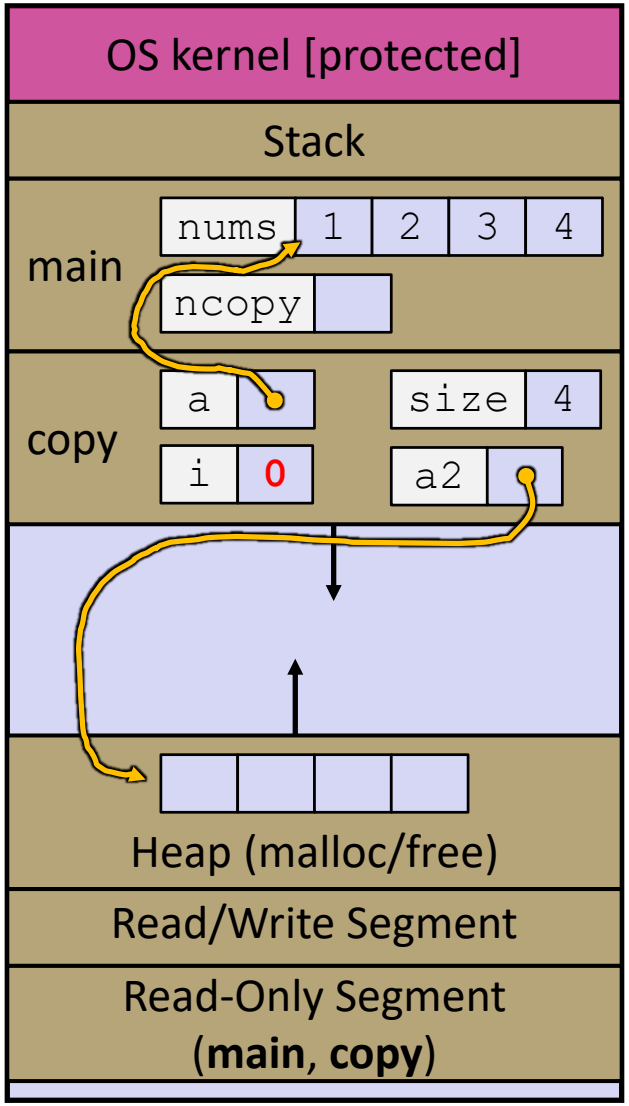


Heap and Stack Example

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 EXIT_SUCCESS;
}
```

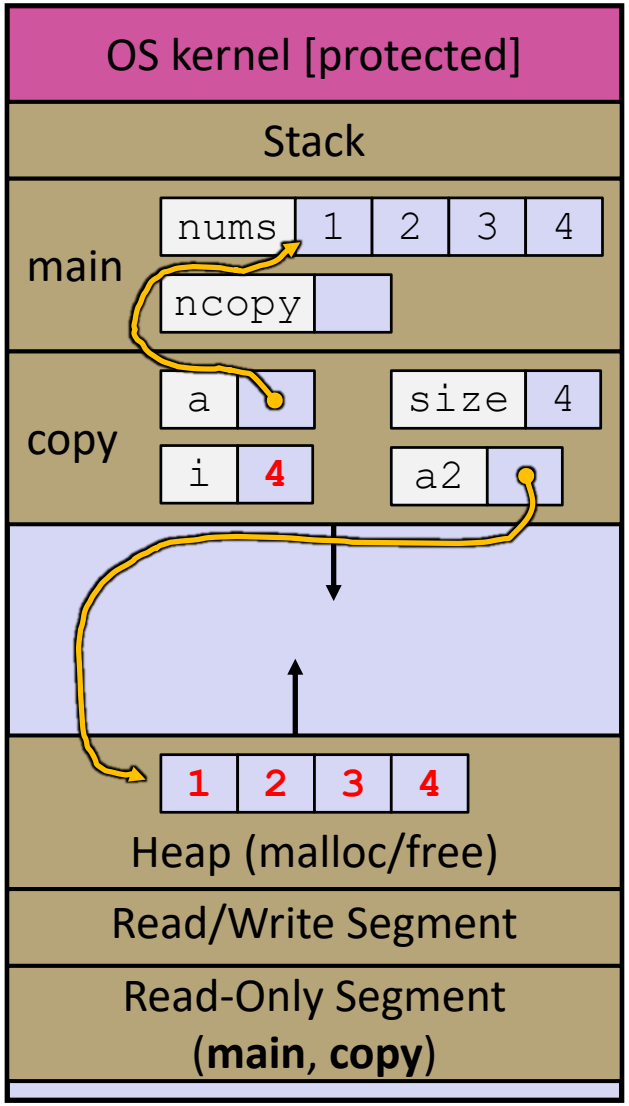


Heap and Stack Example

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 EXIT_SUCCESS;
}
```

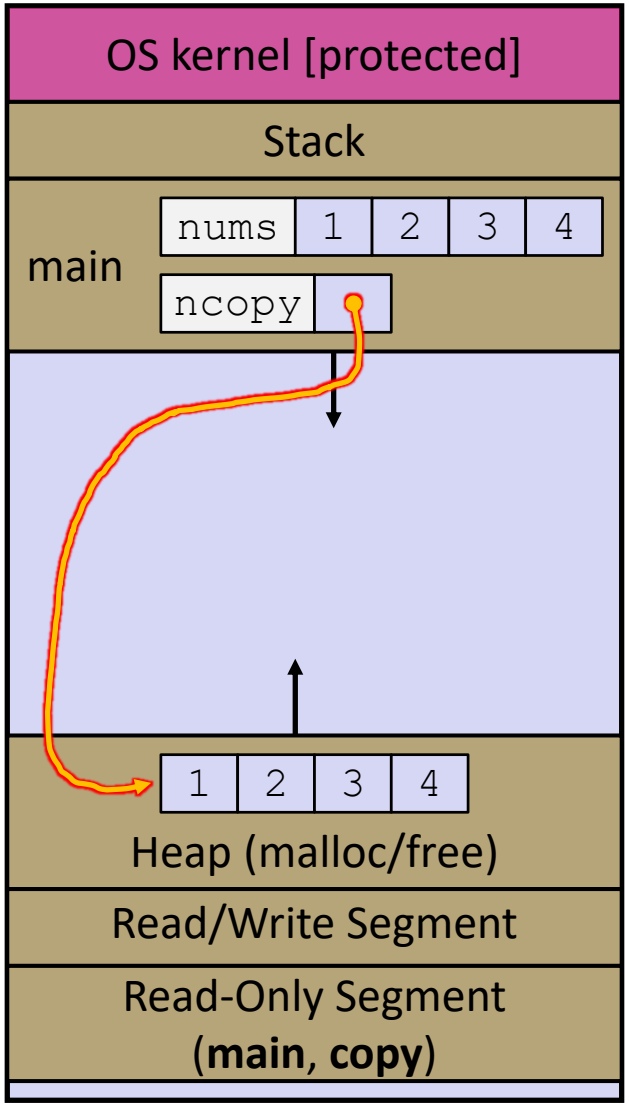


Heap and Stack Example

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 EXIT_SUCCESS;
}
```

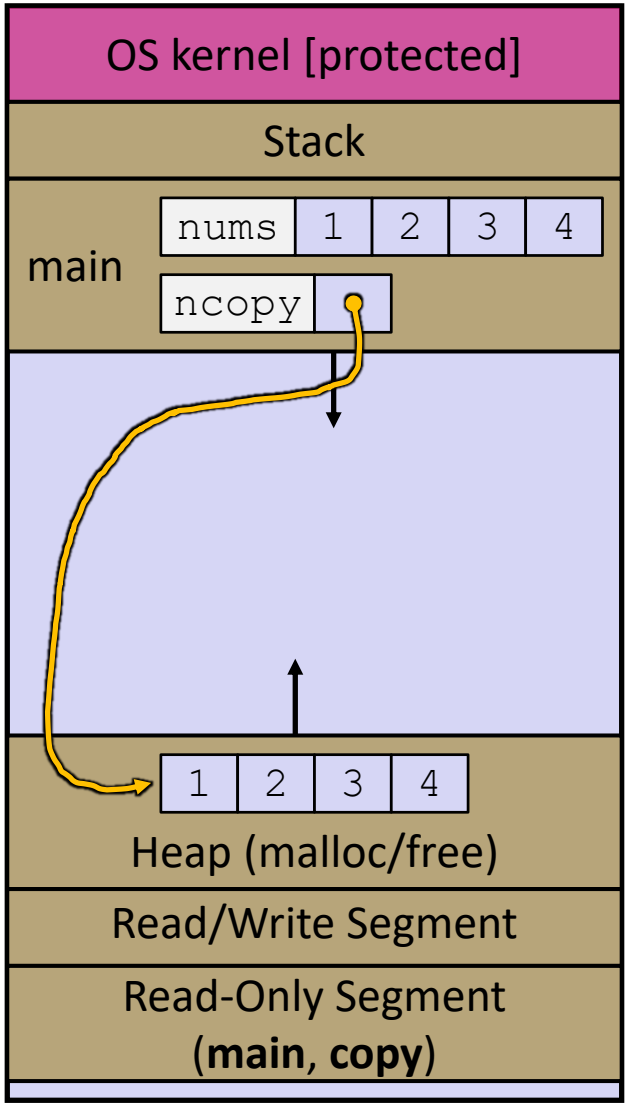


Heap and Stack Example

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 EXIT_SUCCESS;
}
```

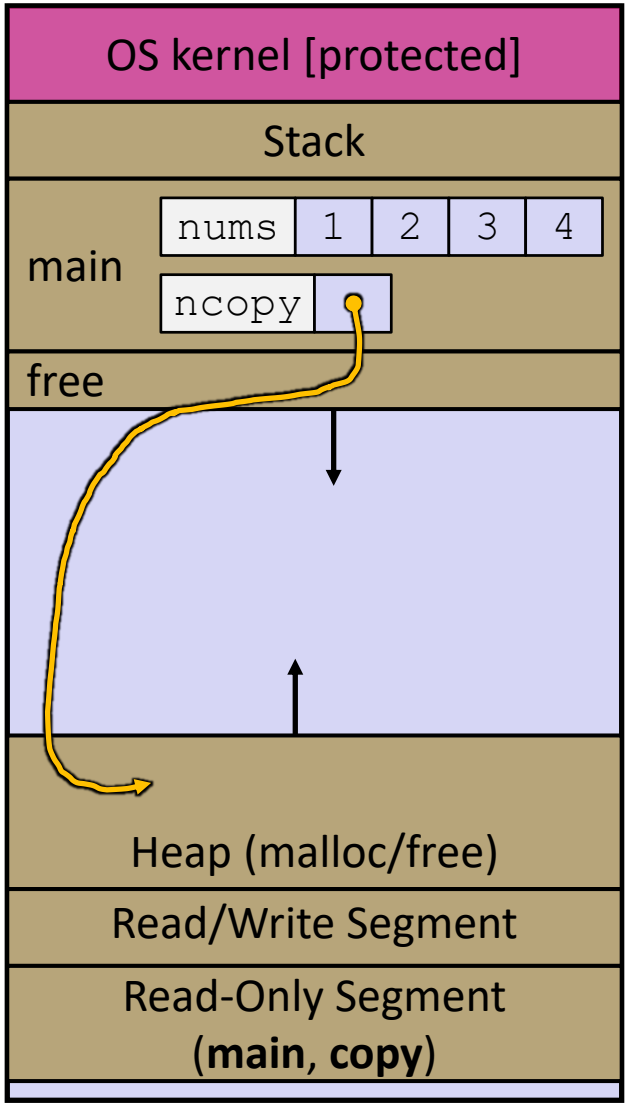


Heap and Stack Example

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 EXIT_SUCCESS;
}
```



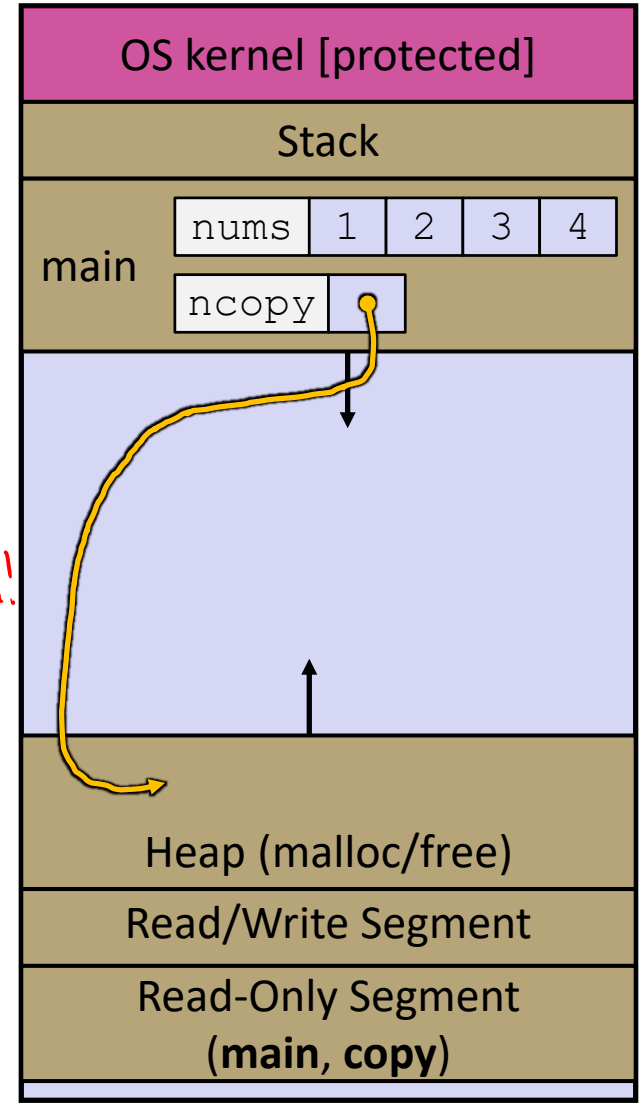
Heap and Stack Example

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 EXIT_SUCCESS;
}
```

ncopy unchanged!



Poll Everywhere

pollev.com/cse333

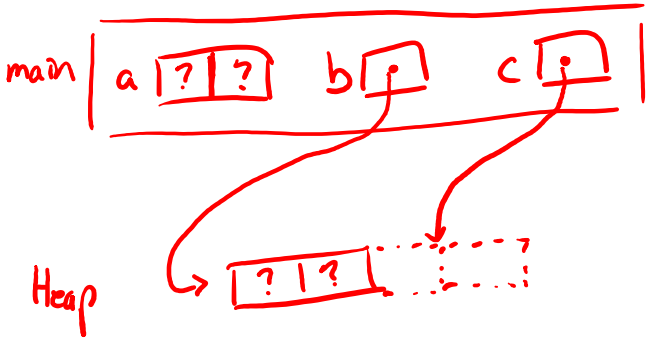
Which line below is first *guaranteed* to cause an error?

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

memcorrupt.c

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

int main(int argc, char** argv) {
  int a[2];
  int* b = 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;
}
```

write past end of array
using mystery data, didn't check for NULL
pointer past allocated block
free stack address
freeing previously-freed address
using freed pointer



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: 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 memory and performance repercussions for *long-lived* programs

Lecture Outline

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

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};
```

type name

works even if fields are different types

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

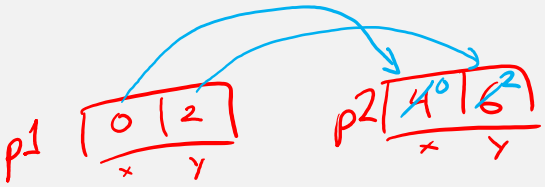
```
struct Point {
  float x, y;
};

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 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};
```

type

name

not recommended

expands similarly to: unsigned int n, *p; ⟺ unsigned int n; unsigned int *p;

typedef struct point_st Point PointPtr

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

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

structarg.c

```
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: (1,1)
  DoubleXWorks(&a);
  printf("(%d,%d)\n", a.x, a.y);    // prints: (2,1)
  return EXIT_SUCCESS;
}
```

only modifies local copy

modifies caller's data

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
}
```

OK to return local struct because values can be assigned to another struct

complexstruct.c

Pass Copy of Struct or Pointer?

- Value passed: passing a pointer is cheaper and takes less space unless struct is small (≤ sizeof(void*))
- Field access: indirect accesses through pointers are a bit more expensive and can be harder for compiler to optimize dereference = access memory
- For small stucts (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

Discussion Activity

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

- Assume that all `Node` instances are dynamically-allocated and that we are designing a **`Pop`**`(Node* head)` function that removes the first node and returns it, discuss:
  - Should the return type be `Node` or `Node*`?
  - Should we free the popped `Node` or not?

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);
```