Pointers, The Heap

CSE 333 Fall 2023

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Relevant Course Information (1/3)

- Exercise 1 due tonight (10/2) by 10pm
- Exercise 2 out today and due Thursday (10/5) by 10pm
- Exercise grading
  - Autograder scores visible immediately after deadline; sample solutions released same day as (late) deadline
  - Grades (out of 8):
    - Autograder: Compilation (1), Correctness (3), Linter (1), Valgrind (1)
    - Manual: Other Style (2)
  - Style things to watch for:
    - FOLLOW THE SPEC (especially the Style Guide section)
    - Check the Google C++ Style Guide
    - Make a judgment call and document
  - Keep style tips in mind, as you will need to use them in hw

Relevant Course Information (2/3)

- hw0 due Tuesday *before* 10:00 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 will be released by tomorrow
  - 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 (3/3)

- Documentation:
  - man pages, books
  - Reference websites: `cplusplus.org`, `man7.org`, `gcc.gnu.org`, etc.

- Folklore:
  - Google-ing, Stack Overflow, that rando in lab, ChatGPT

- Tradeoffs? Relative strengths & weaknesses?

Output Parameters

Warning: Misuse of output parameters is *the* largest cause of errors in this course!

- Output parameter
  - A pointer parameter used to store (via dereference) a function output *outside* of the function's stack frame
    - Typically points to/modifies something in the Caller's scope
  - Useful if you want to have multiple return values

- Setup and usage:
  1) Caller creates space for the data (*e.g.*, `type var;`)
  2) Caller passes in a pointer to Callee (*e.g.*, `&var`)
  3) Callee takes in output parameter (*e.g.*, `type* outparam`)
  4) Callee uses parameter to set output (*e.g.*, `*outparam = value;`)
  5) Caller accesses output via modified data (*e.g.*, `var`)

Poll Everywhere

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Which is an *incorrect* way to invoke GenerateString()?

- Of the working ways, which would be preferred?

```
void GenerateString(char** output) {
  *output = "Hello there\n";
}
```

A.

```
char** result;
GenerateString(result);
printf("%s", *result);
```

B.

```
char* str;
char** result = &str;
GenerateString(result);
printf("%s", str);
```

C.

```
char* result[1] = {NULL};
GenerateString(result);
printf("%s", result[0]);
```

D.

```
char* result;
GenerateString(&result);
printf("%s", result);
```

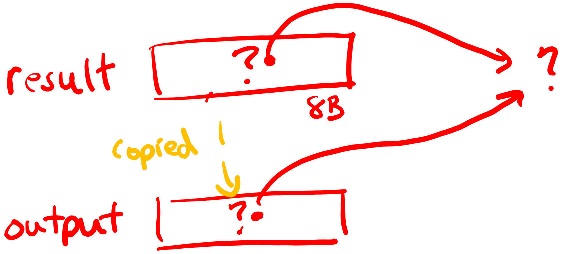
E. We're lost…

Which is an *incorrect* way to invoke generateString()?

```
void GenerateString(char** output) {
  *output = "Hello there\n";
}
```

A.

```
char** result;  //uninitialized!
GenerateString(result);
printf("%s", *result);
```

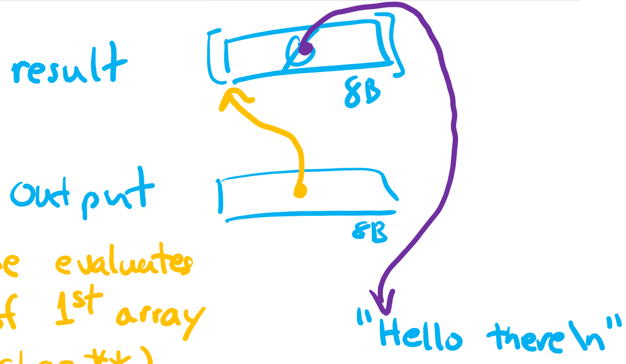


dereferencing mystery data is likely to cause unexpected behavior (e.g., segfault)

C.

array of 1 char*

```
char* result[1] = {NULL};
GenerateString(result);
printf("%s", result[0]);
```



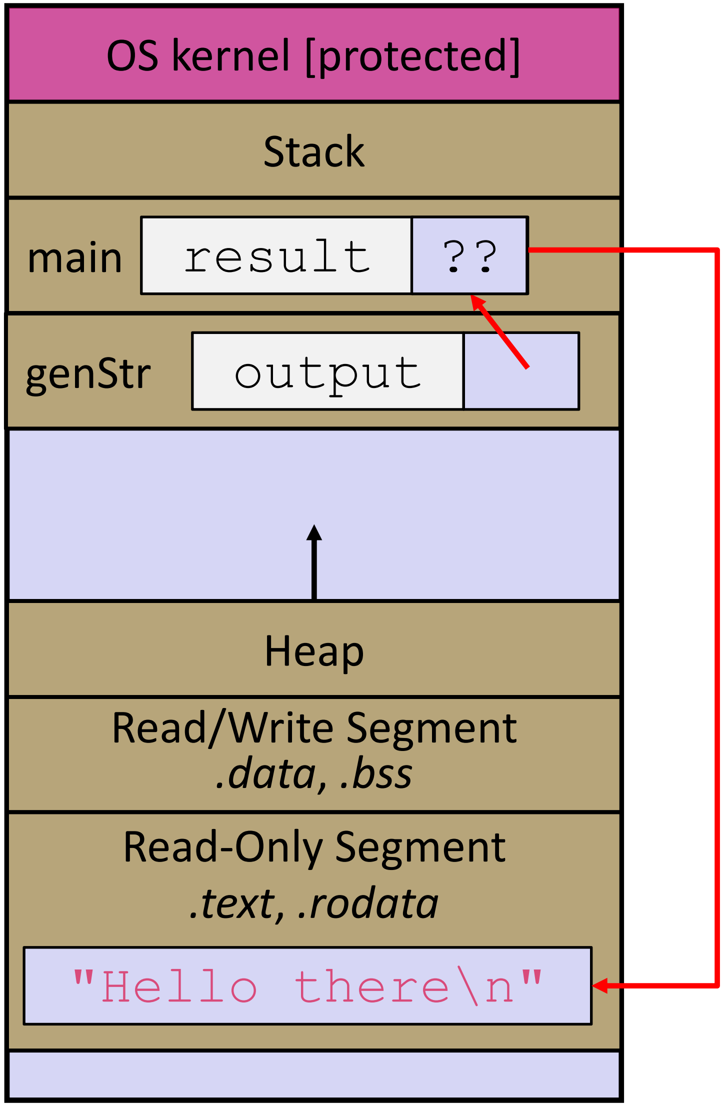
array name evaluates to address of 1st array element (char**)

dereferencing output lets us update result[0]

Preferred Usage

Note: Arrow points to *next* instruction.

genstr.c



D.

```
void GenerateString(char** output);

int main(int argc, char** argv) {
  char* result;
  GenerateString(&result);
  printf("%s", result);

  return EXIT_SUCCESS;
}

void GenerateString(char** output) {
  *output = "Hello there\n";
}
```

- ✓ Works correctly (unlike A)
- ✓ Minimizes memory usage (unlike B)
- ✓ Intent is clear (unlike C)

Lecture Outline

- **Function Pointers**
- Heap-allocated Memory
  - `malloc()` and `free()`
  - Memory leaks

Function Pointers

jmp foo → address → PC

- Based on what you know about assembly, what is a function name, really? label → address
  - Can use pointers that store addresses of functions!

function pointer → int (*fp)(int) = foo;

function prototype → int foo(int);

function prototype → int *fp(int)

- Generic format: pointer!

```
returnType (* name)(type1, …, typeN)
```

  - Looks like a function prototype with extra * in front of name
  - Why are parentheses around (* name) needed? to differentiate it from a function prototype

dereference

- Using the function:

```
(*name)(arg1, …, argN)
```

  - Calls the pointed-to function with the given arguments and return the return value

Function Pointer Example

- `Map()` performs operation on each element of an array

functions that "fit" this function pointer

```
#define LEN 4

int Negate(int num) {return -num;}
int Square(int num) {return num * num;}

// perform operation pointed to on each array element
void Map(int a[], int len, int (* op)(int n)) {
  for (int i = 0; i < len; i++) {
    a[i] = (*op)(a[i]);  // dereference function pointer
  }
}

int main(int argc, char** argv) {
  int arr[LEN] = {-1, 0, 1, 2};
  int (* op)(int n);    // function pointer called 'op'
  op = Square;     // function name returns addr (like array)
  Map(arr, LEN, op);
  ...
```

funcptr parameter

funcptr dereference

funcptr definition

funcptr assignment

could directly use function name here (square)

map.c

Function Pointer Example

- C allows you to omit & on a function name (like arrays) and omit * when calling pointed-to function

```
#define LEN 4

int Negate(int num) {return -num;}
int Square(int num) {return num * num;}

// perform operation pointed to on each array element
void Map(int a[], int len, int (* op)(int n)) {
  for (int i = 0; i < len; i++) {
    a[i] = op(a[i]);  // dereference function pointer
  }
}

int main(int argc, char** argv) {
  int arr[LEN] = {-1, 0, 1, 2};
  Map(arr, LEN, Square);
  ...
```

implicit funcptr dereference (no * needed)

no & needed for func ptr argument

Lecture Outline

- Function Pointers
- **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;
}
```

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()

STYLE TIP

- 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
```

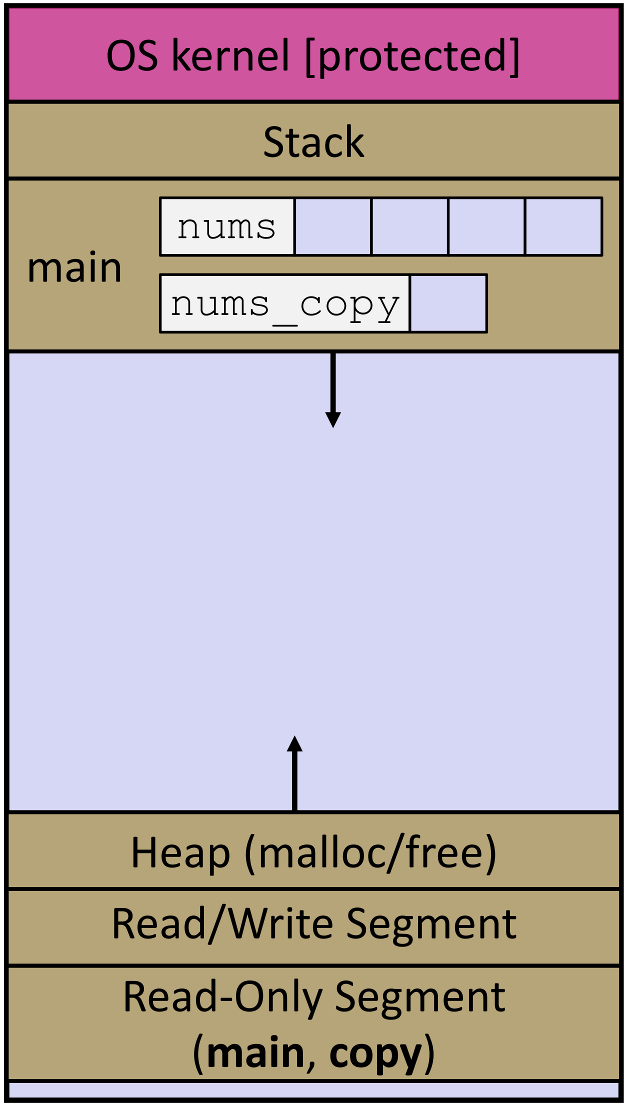
(debugging/non-performance critical code only)

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



OS kernel [protected]

Stack

main

nums

nums_copy

Heap (malloc/free)

Read/Write Segment

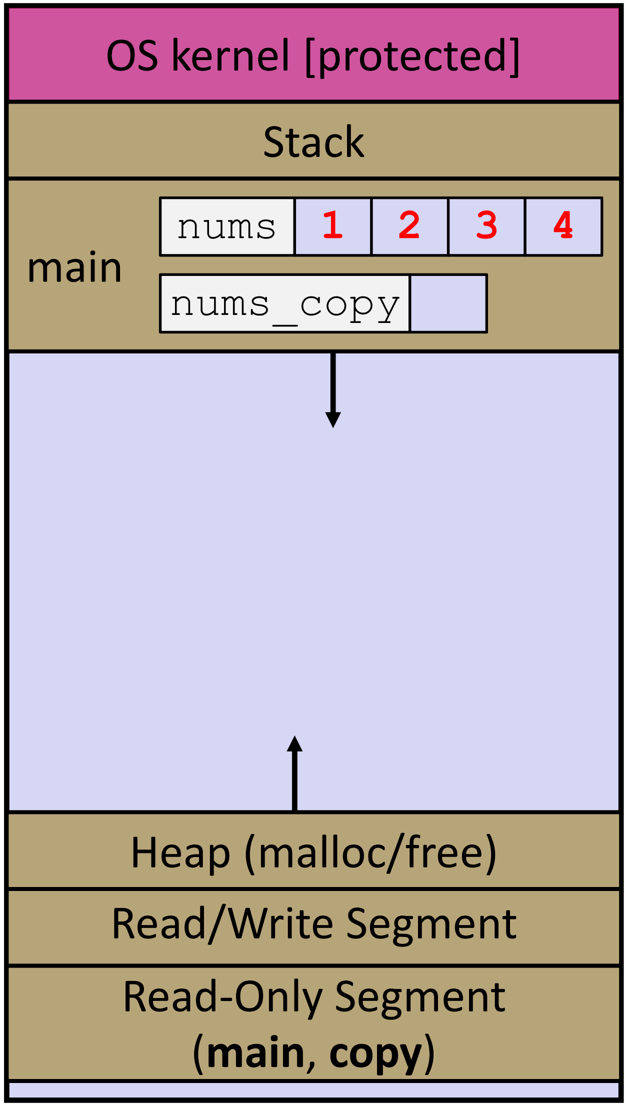
Read-Only Segment (**main, copy**)

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

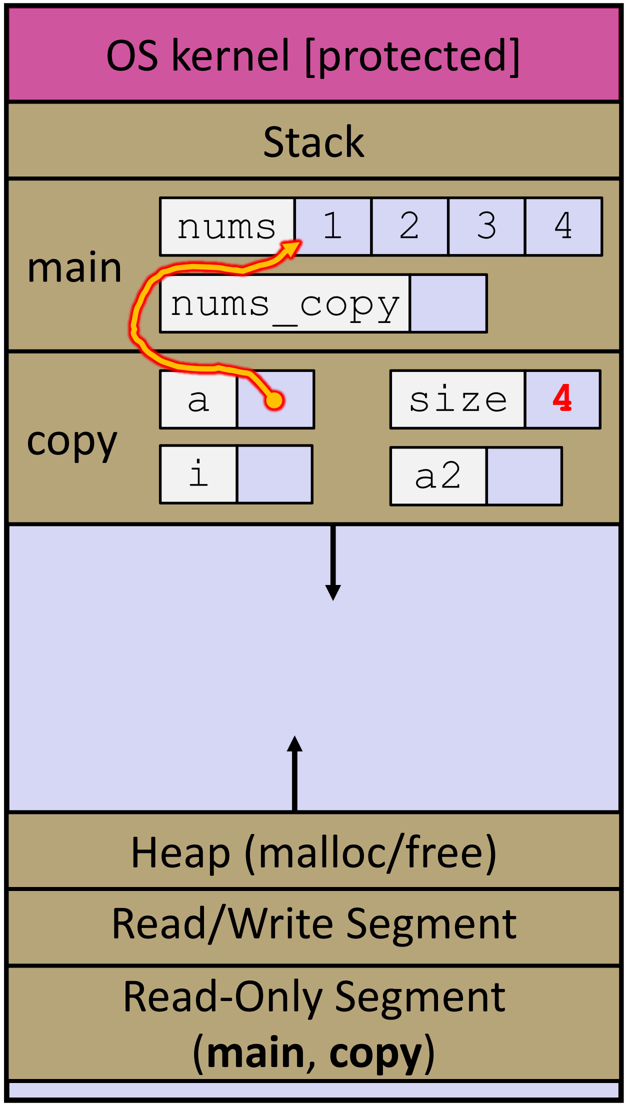


Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

```
#include <stdlib.h>
                 actually a  int*
int* Copy(int a[], int size) {
  int i, *a2;
                          4           4
  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* nums_copy = Copy(nums, 4);
  // .. do stuff with the array ..
  free(nums_copy);
  return EXIT_SUCCESS;
}
```



Heap and Stack Example

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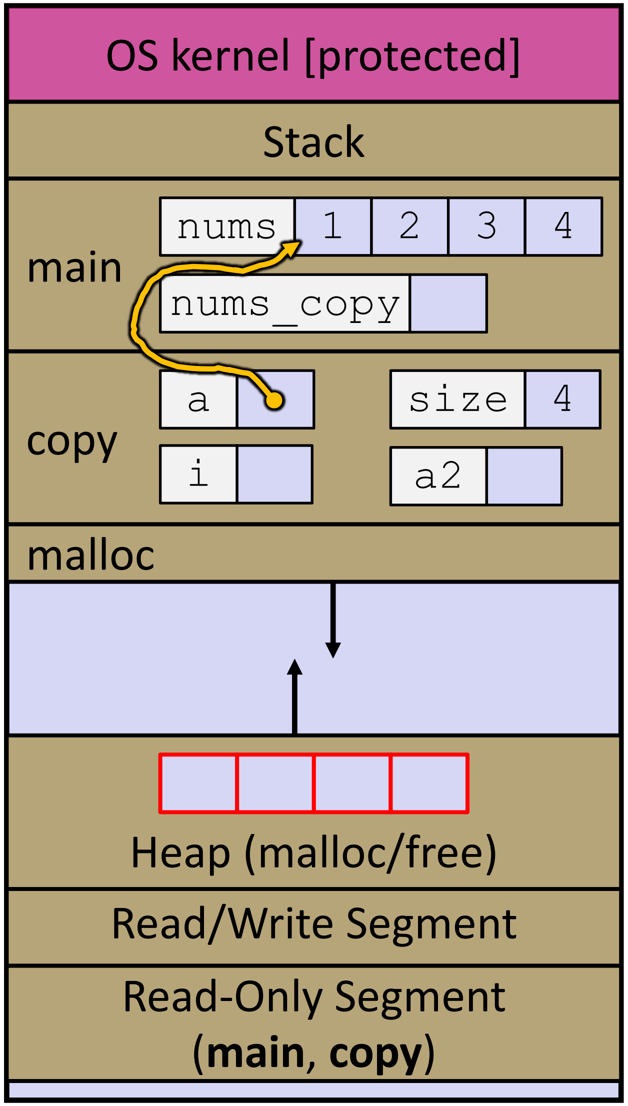
arraycopy.c

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



Heap and Stack Example

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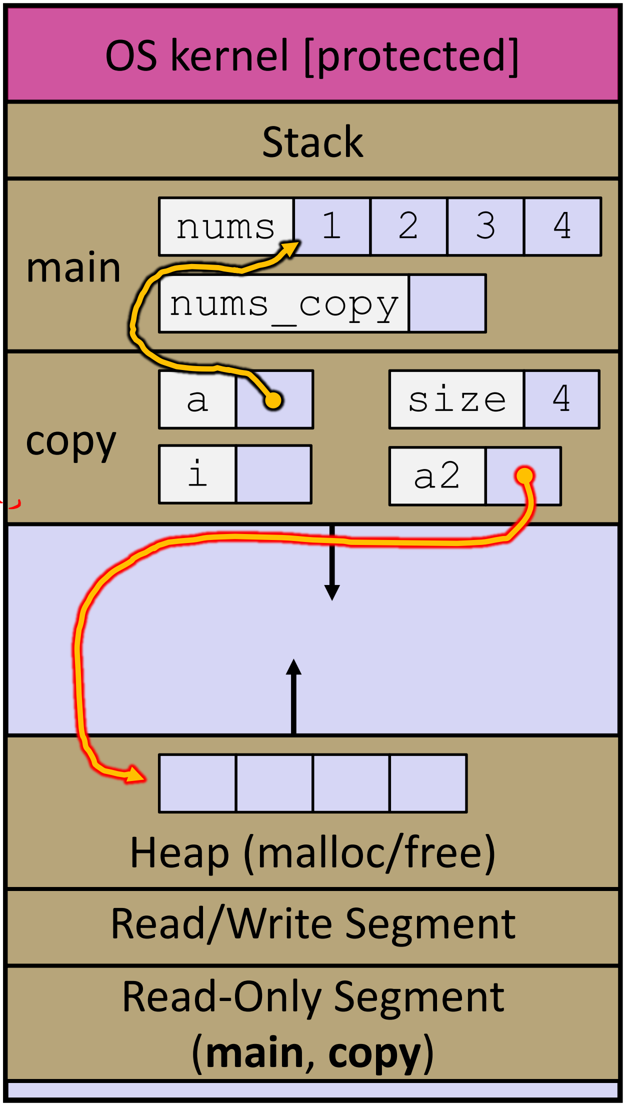
```
#include <stdlib.h>

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

if succeeded, otherwise NULL



Heap and Stack Example

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

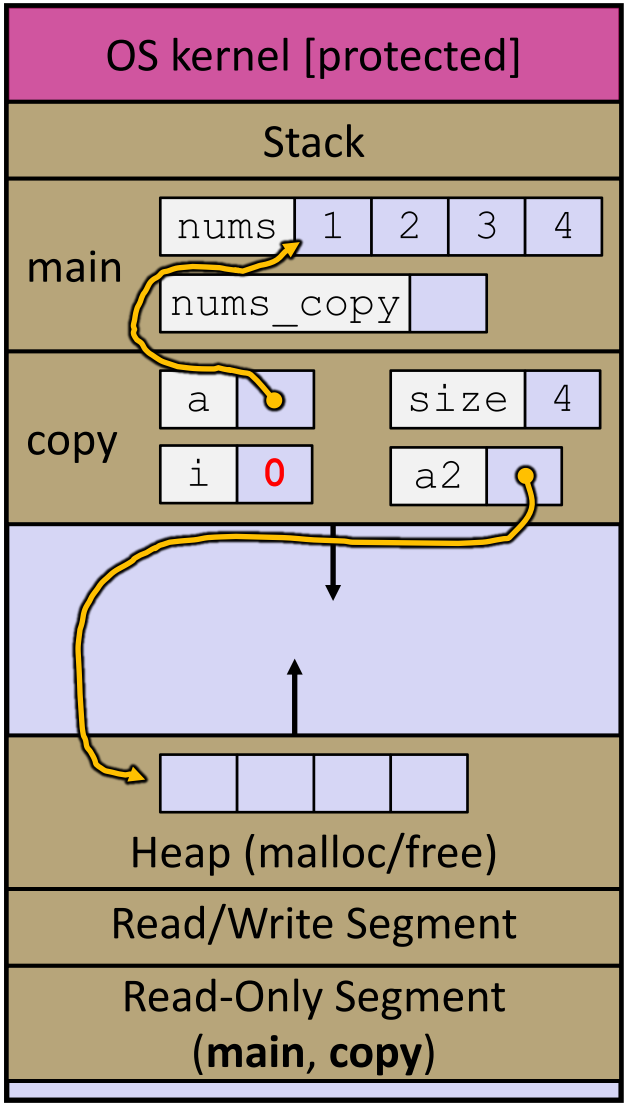

Heap and Stack Example

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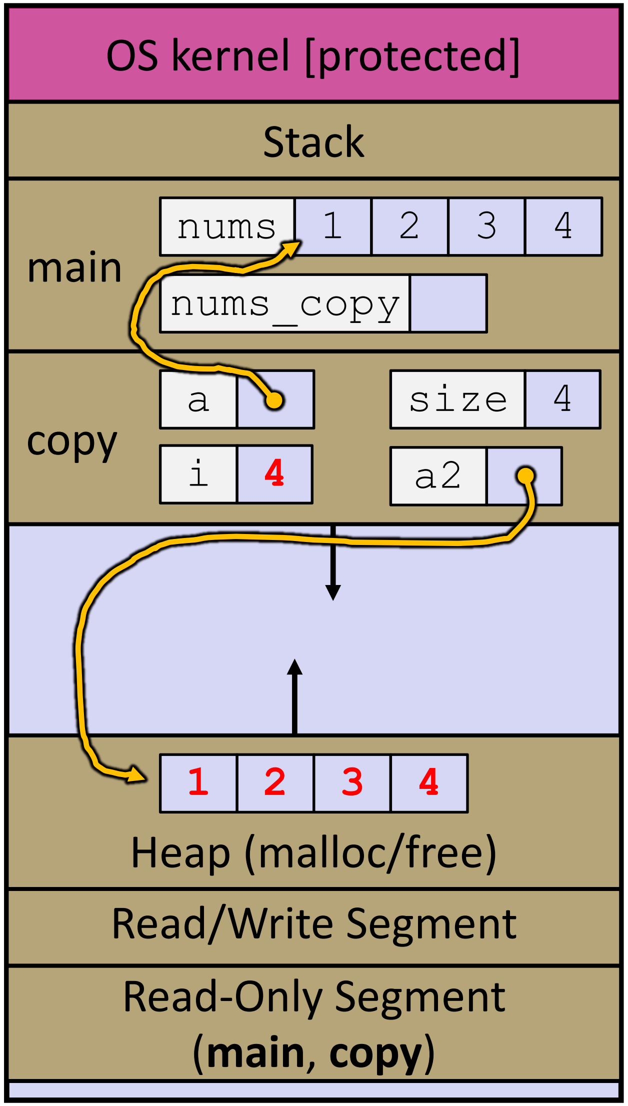
arraycopy.c

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



Heap and Stack Example

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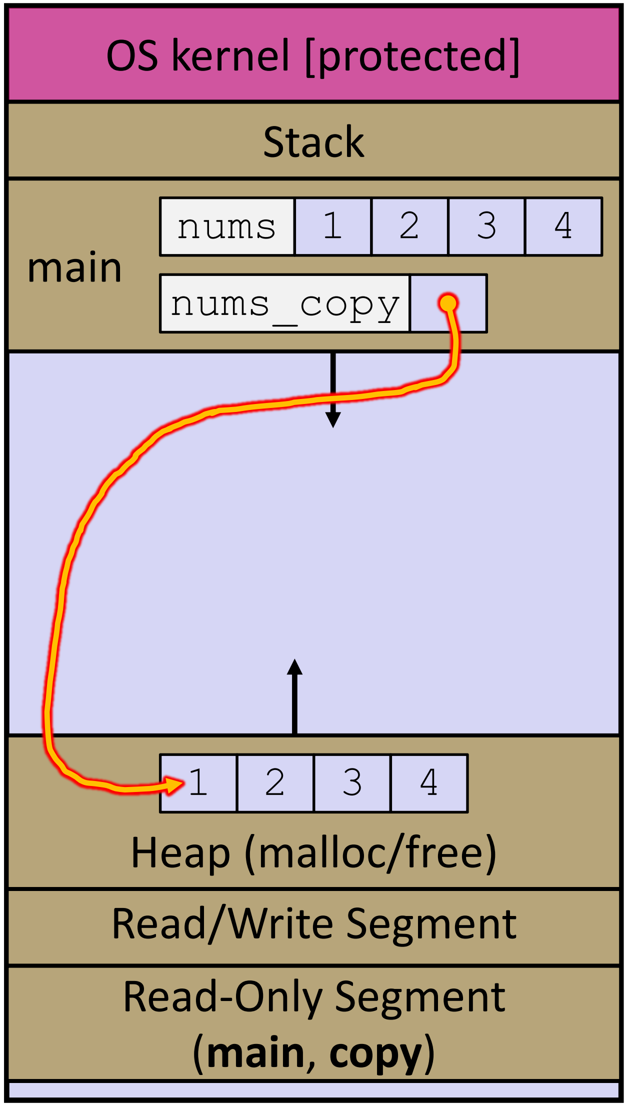
arraycopy.c

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

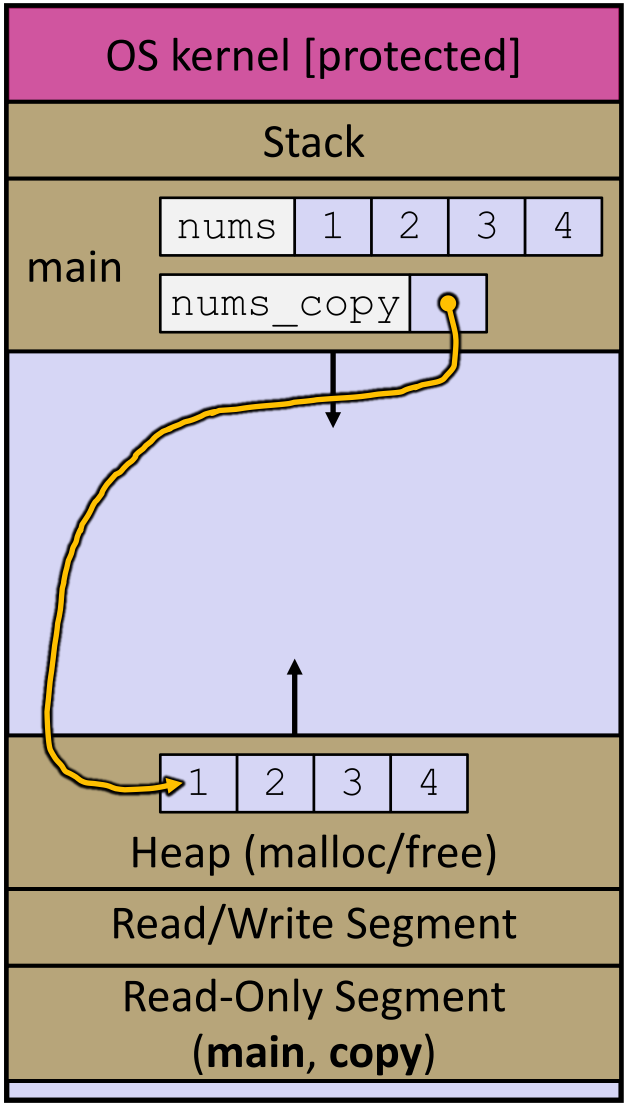


Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

```
#include <stdlib.h>

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

  a2 = (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* nums_copy = Copy(nums, 4);
  // .. do stuff with the array ..
  free(nums_copy);
  return EXIT_SUCCESS;
}
```

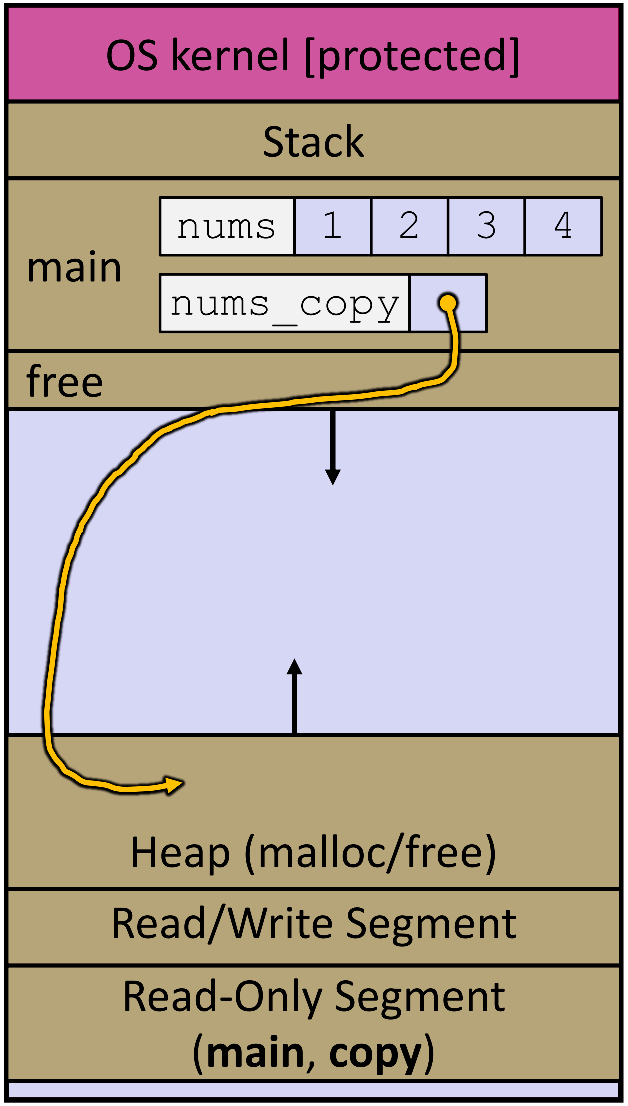


Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

```
#include <stdlib.h>

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

  a2 = (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* nums_copy = Copy(nums, 4);
  // .. do stuff with the array ..
  free(nums_copy);
  return EXIT_SUCCESS;
}
```

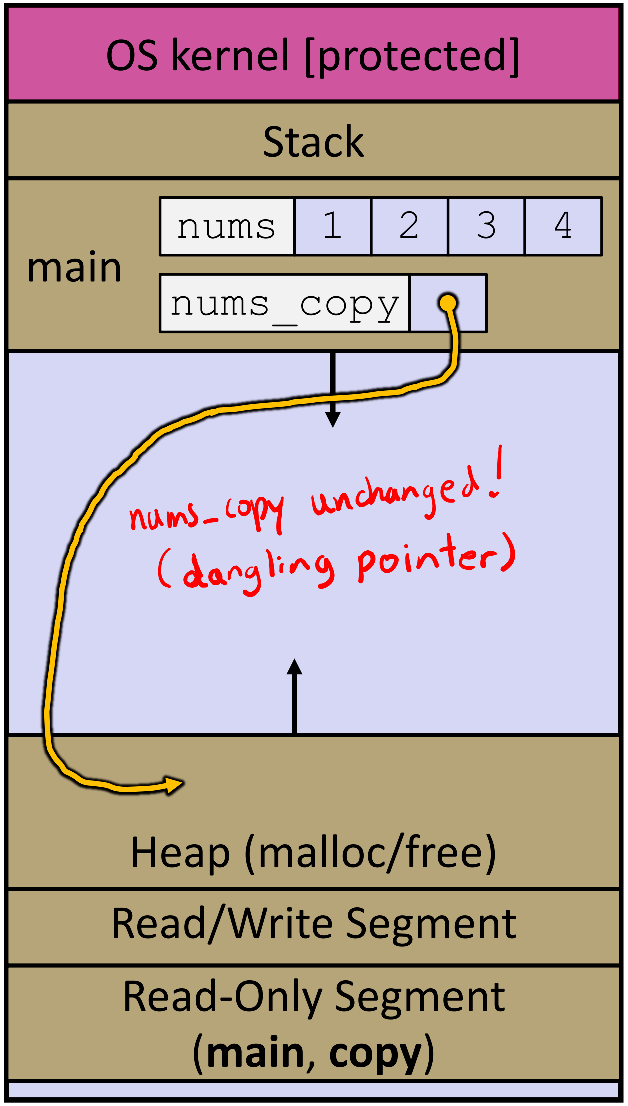


Heap and Stack Example

Note: Arrow points to *next* instruction.

arraycopy.c

```
#include <stdlib.h>

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

  a2 = (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* nums_copy = Copy(nums, 4);
  // .. do stuff with the array ..
  free(nums_copy);
  return EXIT_SUCCESS;
}
```



OS kernel [protected]

Stack

main

nums	1	2	3	4

nums_copy

nums_copy unchanged!
(dangling pointer)

Heap (malloc/free)

Read/Write Segment

Read-Only Segment
(main, copy)

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Which line will first cause a *guaranteed* error or undefined behavior?

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 = (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;
}
```

Line 1: write past end of array

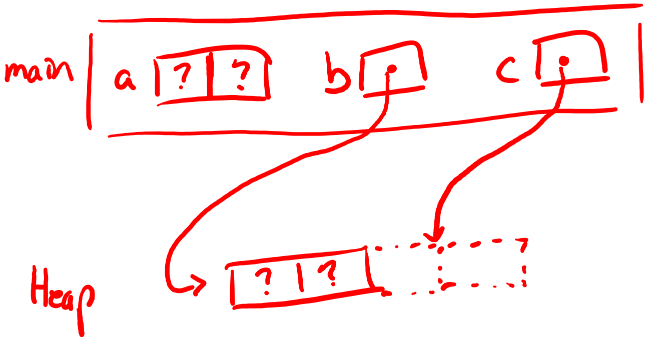
Line 2: using mystery data, didn't check for NULL

Line 3: pointer past allocated block

Line 4: free stack address

Line 6: freeing previously-freed address

Line 7: 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 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

Extra Exercise #1

- Write a function that:
  - Accepts a function pointer and an integer as arguments
  - Invokes the pointed-to function with the integer as its argument

Extra Exercise #2

- Write a function that:
  - Accepts a string as a parameter
  - Returns:
    - The first white-space separated word in the string as a newly-allocated string
    - AND the size of that word

Extra Exercise #3

- Write a function that:
  - Arguments: [1] an array of ints and [2] an array length
  - Malloc's an `int*` array of the same element length
  - Initializes each element of the newly-allocated array to point to the corresponding element of the passed-in array
  - Returns a pointer to the newly-allocated array