More Pointers, The Heap

CSE 333 Winter 2020

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Teaching Assistants:

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Rehaan Bhimar	Renshu Gu	Travis McGaha
Zachary Keyes		

Administrivia

- Exercise 2 out today and due Monday morning

- Exercise grading
  - We will do our best to keep up
  - Things to watch for:
    - Input sanity check
    - No functional abstraction (single blob of code)
    - Formatting funnies (*e.g.* tabs instead of spaces)
  - Grades:
    - Autograder [0 to 3], Style [-2 to +0.1] – Overall [0, 1, 2, 3, 3.1]

Administrivia

- Homework 0 due Monday
  - Logistics and infrastructure for projects
    - `clint` and `valgrind` are useful for exercises, too
  - Should have set up an SSH key and cloned GitLab repo by now
    - Do this ASAP so we have time to fix things if necessary
- Homework 1 out later today, due in 2 weeks (Thu 1/23)
  - Linked list and hash table implementations in C
  - Get starter code using `git pull` in your course repo
    - Might have "merge conflict" if your local copy has unpushed changes
      - If git drops you into vi(m), `:q` to quit or `:wq` if you want to save changes

Administrivia

- Documentation:
  - man pages, books
  - Reference websites: `cplusplus.org`, `man7.org`, `gcc.gnu.org`, etc.
- Folklore:
  - Google-ing, Stack Overflow, that rando in lab
- Tradeoffs? Relative strengths & weaknesses?

Lecture Outline

- **Pointer Arithmetic**
- Pointers as Parameters
- Pointers and Arrays
- Function Pointers
- Heap-allocated Memory

Pointer Arithmetic

- Pointers are *typed*
  - Tells the compiler the size of the data you are pointing to
  - Exception: `void*` is a generic pointer (*i.e.* a placeholder)
- Pointer arithmetic is scaled by `sizeof(*p)`

  size of the thing being pointed at
  - Works nicely for arrays
  - Does not work on `void*`, since `void` doesn't have a size!
    - Not allowed, though confusingly GCC allows it as an extension ☹
- Valid pointer arithmetic:
  - Add/subtract an integer to/from a pointer
  - Subtract two pointers (within stack frame or malloc block)
  - Compare pointers (<, <=, ==, !=, >, >=), including `NULL`
  - … but plenty of valid-but-inadvisable operations, too

Polling Question

boxarrow2.c

```
int main(int argc, char** argv) {
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];
  int** dp = &p;  // pointer to a pointer

  *(*dp) += 1;
  p += 1;
  *(*dp) += 1;

  return EXIT_SUCCESS;
}
```

At this point in the code, what values are stored in `arr[]`?

- Vote at http://PollEv.com/justinh

0x7fff…78	arr[2]	4
0x7fff…74	arr[1]	3
0x7fff…70	arr[0]	2
0x7fff…68	p	0x7fff…74
0x7fff…60	dp	0x7fff…68

A. {2, 3, 4}

B. {3, 4, 5}

C. {2, 6, 4}

D. {2, 4, 5}

E. We're lost…

Practice Solution

<u>Note</u>: arrow points to *next* instruction to be executed.

boxarrow2.c

```c
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  int arr[3] = {2, 3, 4};
  int* p = &arr[1];
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```

follow arrow, then follow that arrow

```c
  *(*dp) += 1;
  p += 1;
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  return EXIT_SUCCESS;
}
```

address	name	value

address	name	value
0x7fff…78	arr[2]	4
0x7fff…74	arr[1]	~~3~~ 4
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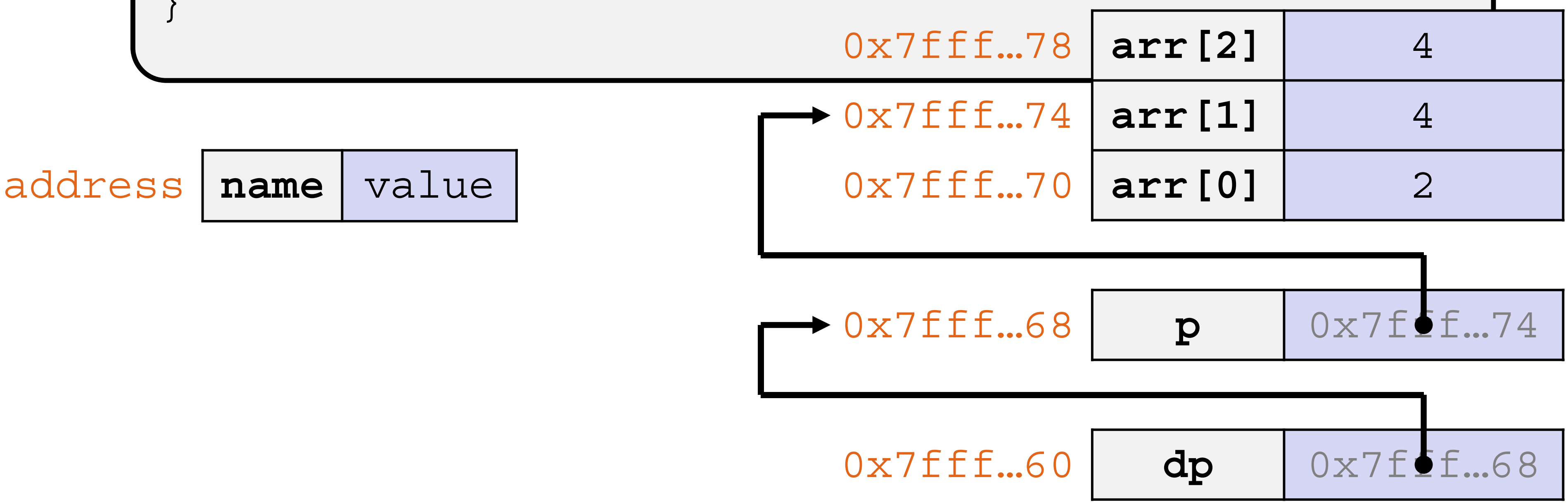

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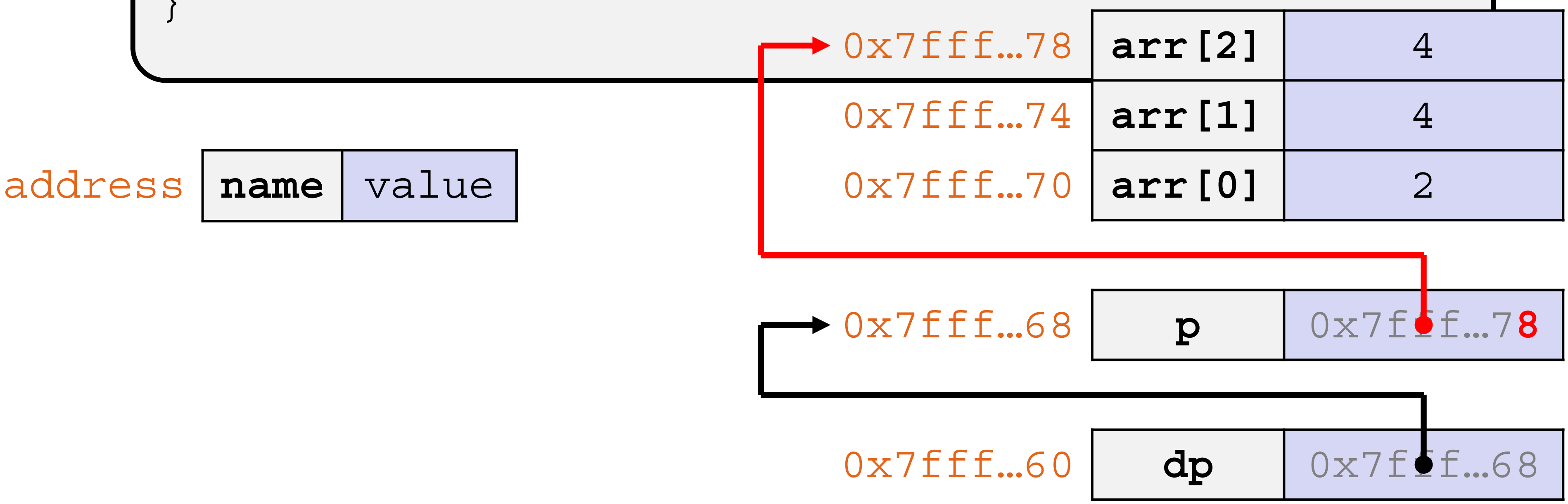

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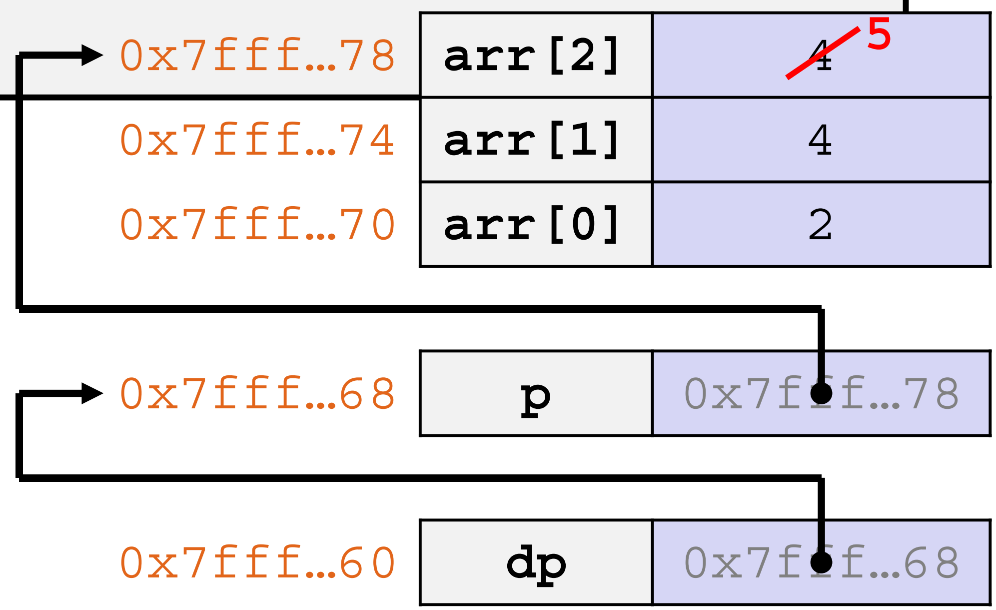
address	name	value



Endianness

- Memory is byte-addressed, so endianness determines what ordering that multi-byte data gets read and stored *in memory*
  - Big-endian: Least significant byte has *highest* address
  - Little-endian: Least significant byte has *lowest* address

(x86-64)

- **Example:** 4-byte data 0xa1b2c3d4 at address 0x100

			0x100	0x101	0x102	0x103		
Big-Endian			a1	b2	c3	d4		
			0x100	0x101	0x102	0x103		
Little-Endian			d4	c3	b2	a1		

Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

1 = 0x00...$\boxed{01}$

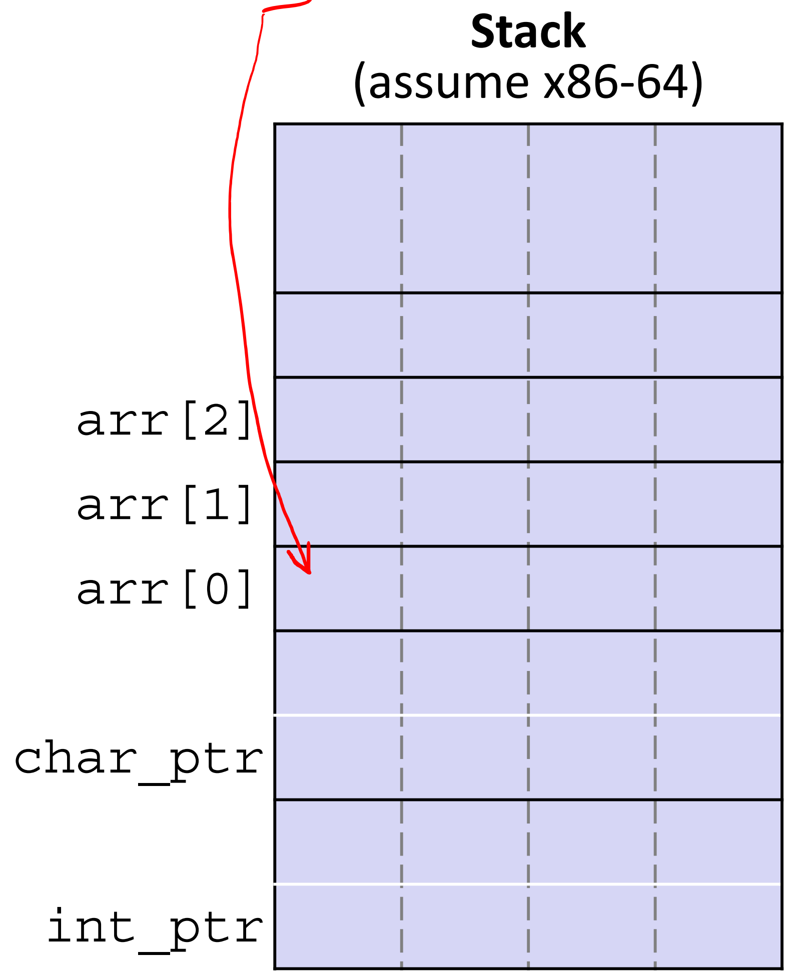
```
int main(int argc, char** argv) {
  int arr[3] = {1, 2, 3};
  int* int_ptr = &arr[0];
  char* char_ptr = (char*) int_ptr;

  int_ptr += 1;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c



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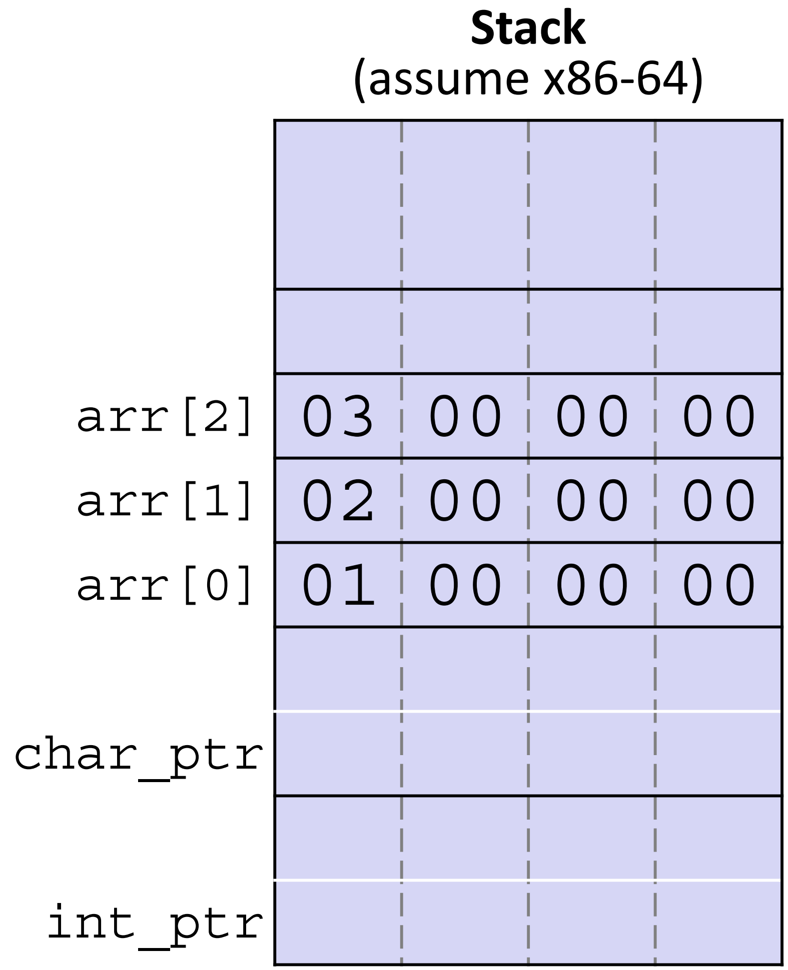
pointerarithmetic.c



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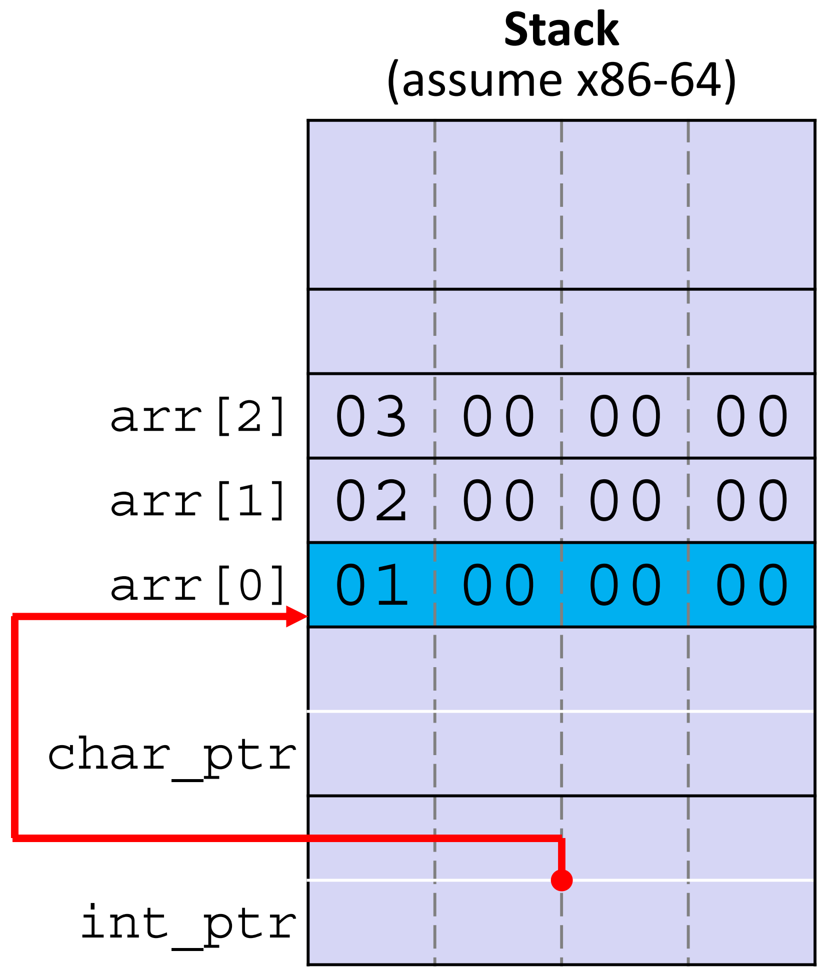

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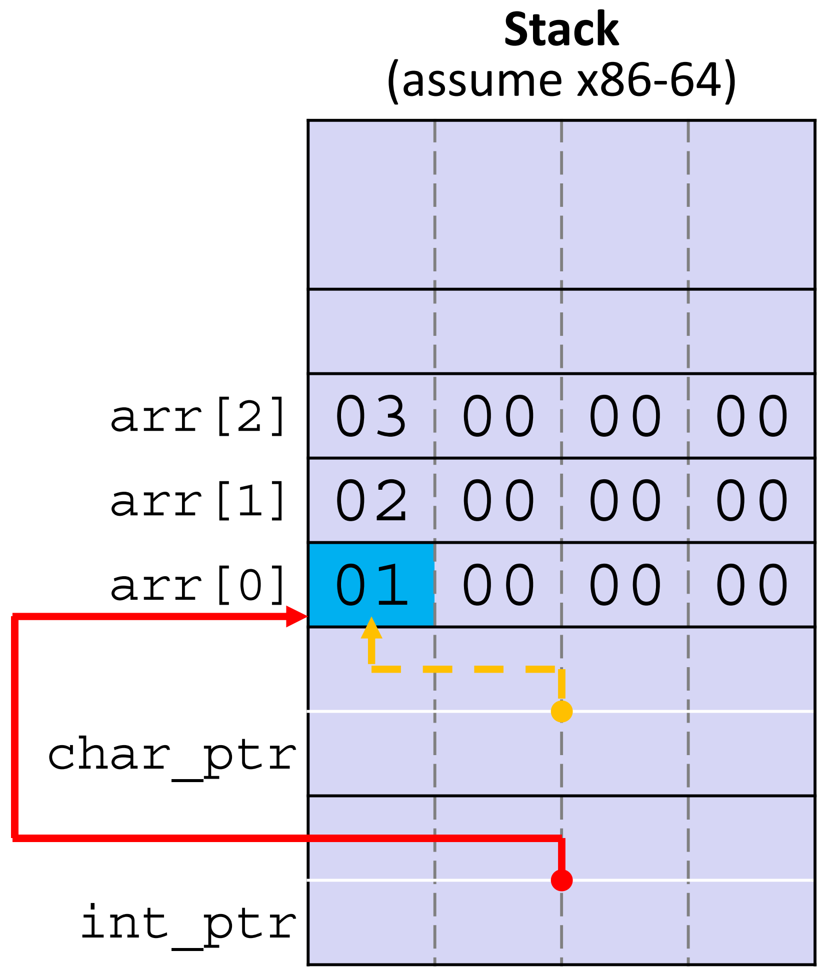
pointerarithmetic.c



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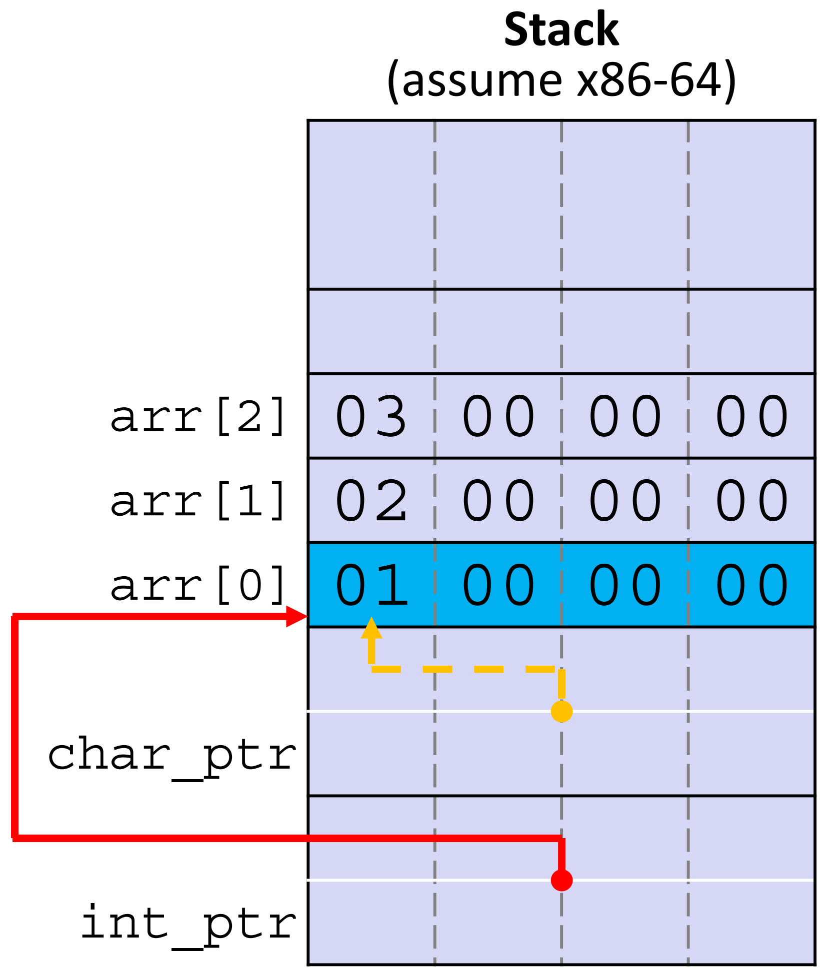
pointerarithmetic.c




```
 int_ptr:  0x0x7ffffffde010
*int_ptr:  1
```

Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

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int main(int argc, char** argv) {
  int arr[3] = {1, 2, 3};
  int* int_ptr = &arr[0];
  char* char_ptr = (char*) int_ptr;

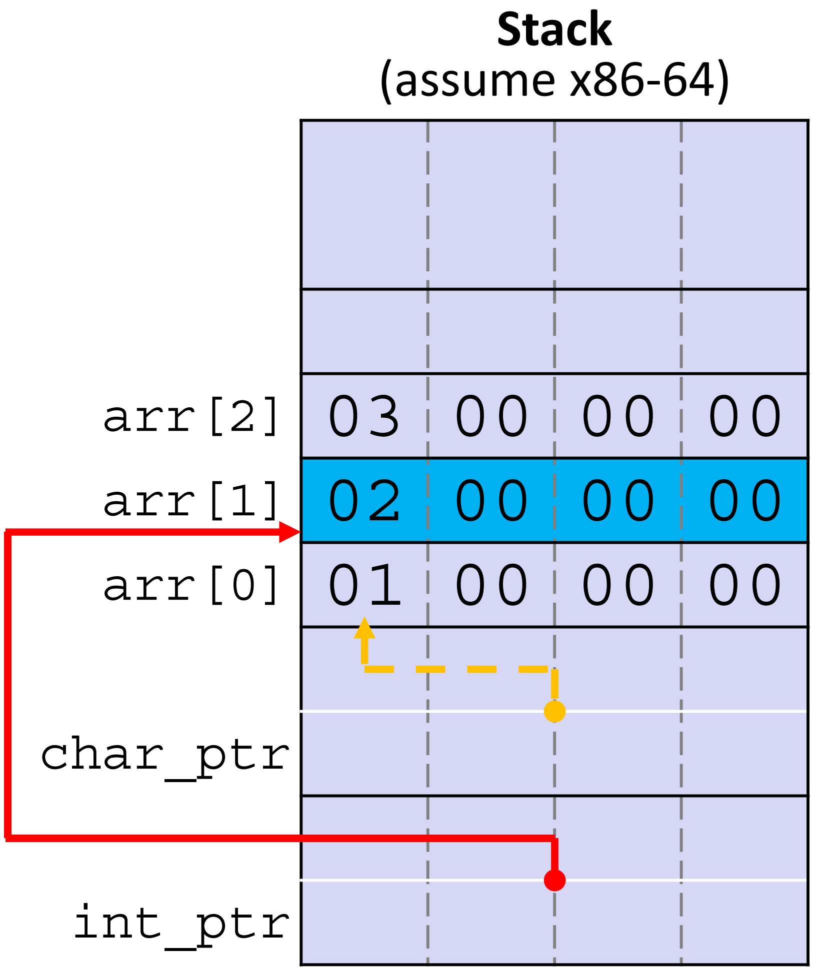
  int_ptr += 1;
  int_ptr += 2;   // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c

```
 int_ptr:   0x0x7ffffffde014
*int_ptr:   2
```



Pointer Arithmetic Example

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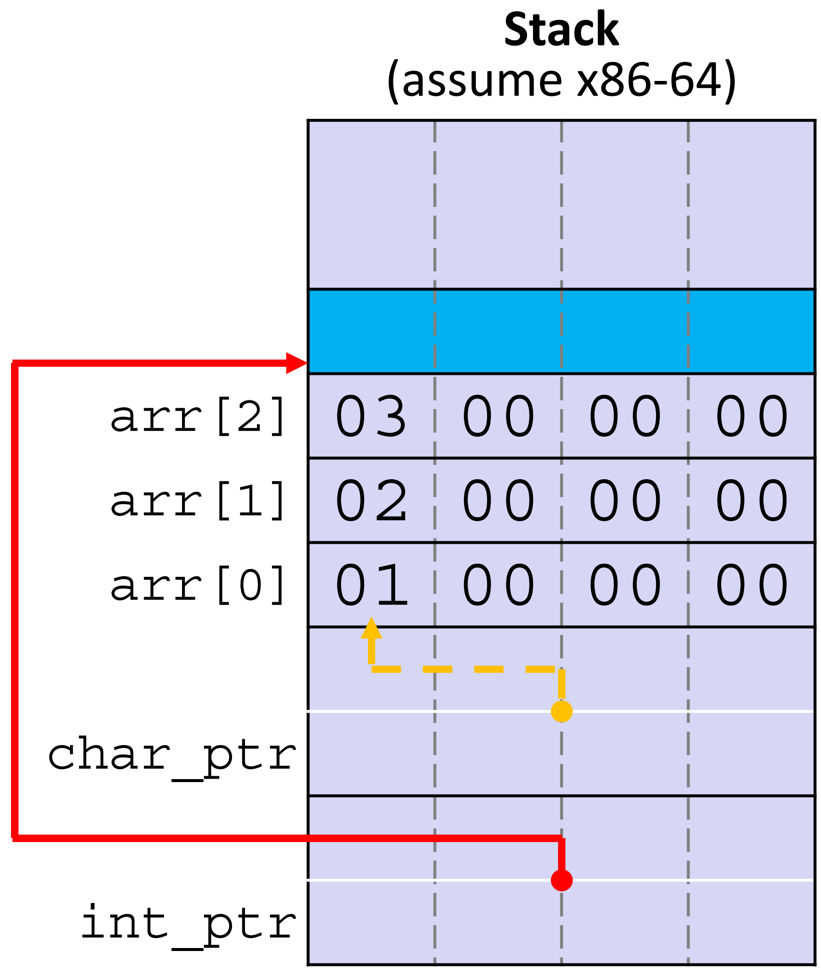
pointerarithmetic.c




```
 int_ptr:  0x0x7ffffffde01C
*int_ptr:  ???
```

Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

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  int* int_ptr = &arr[0];
  char* char_ptr = (char*) int_ptr;

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  return EXIT_SUCCESS;
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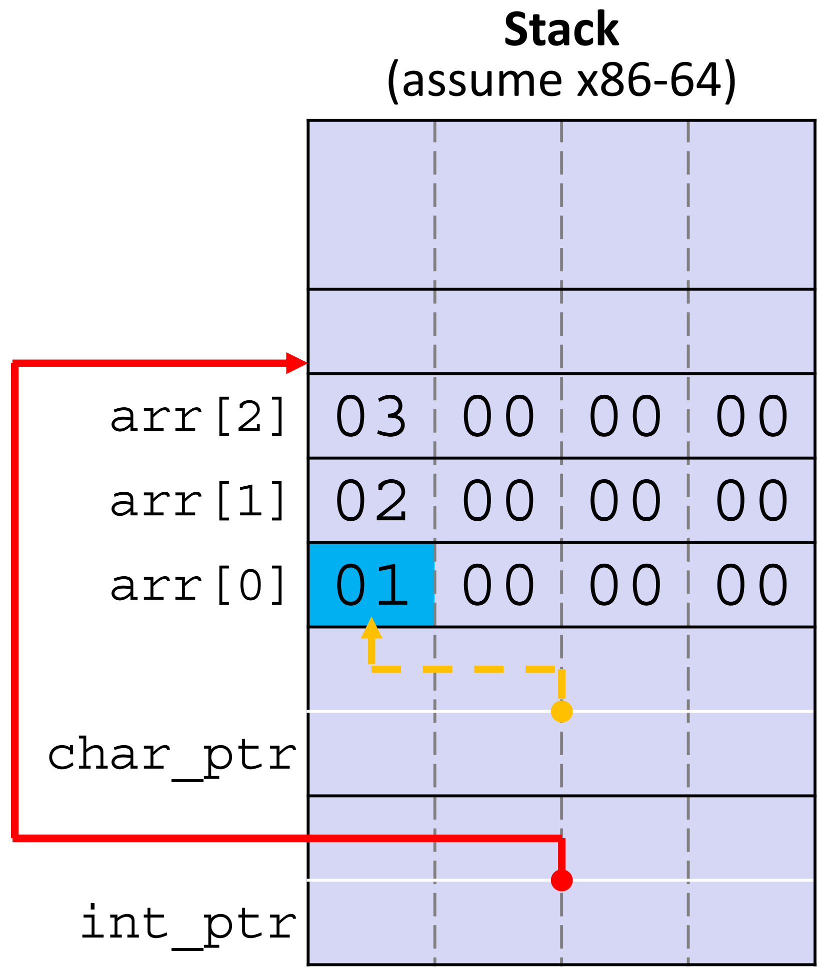
pointerarithmetic.c



char_ptr: 0x0x7ffffffde010
***char_ptr:** 1

Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

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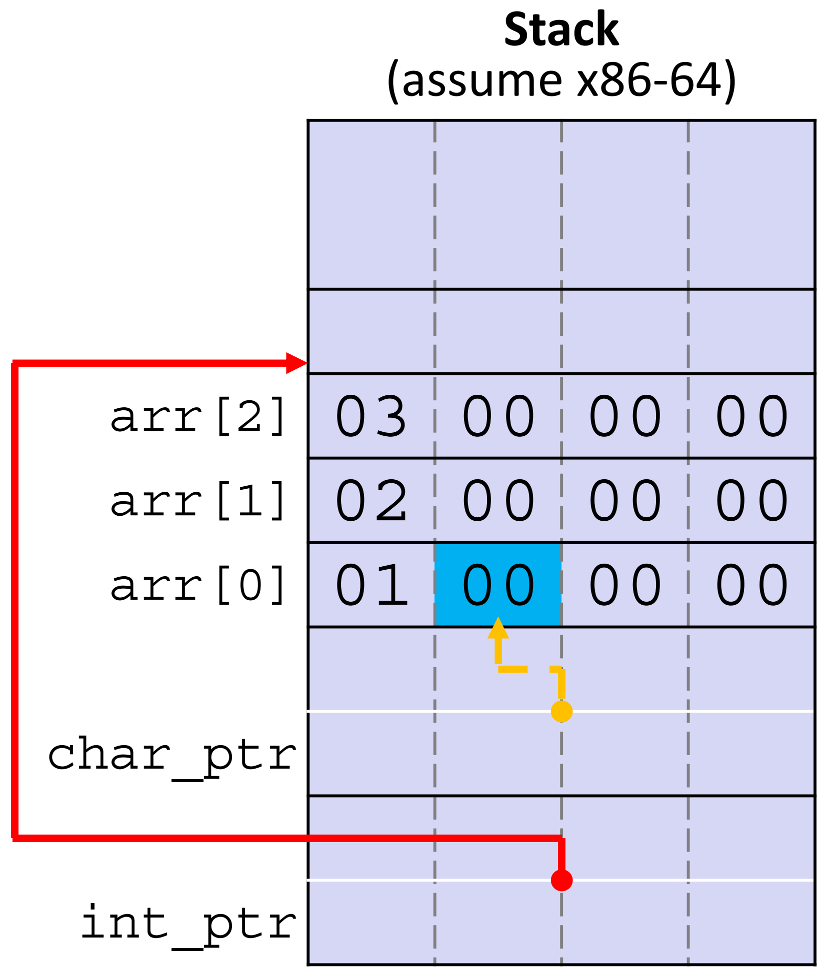
  int_ptr += 1;
  int_ptr += 2;   // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c

```
 char_ptr:   0x0x7ffffffde011
*char_ptr:   0
```



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  int arr[3] = {1, 2, 3};
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  int_ptr += 1;
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  return EXIT_SUCCESS;
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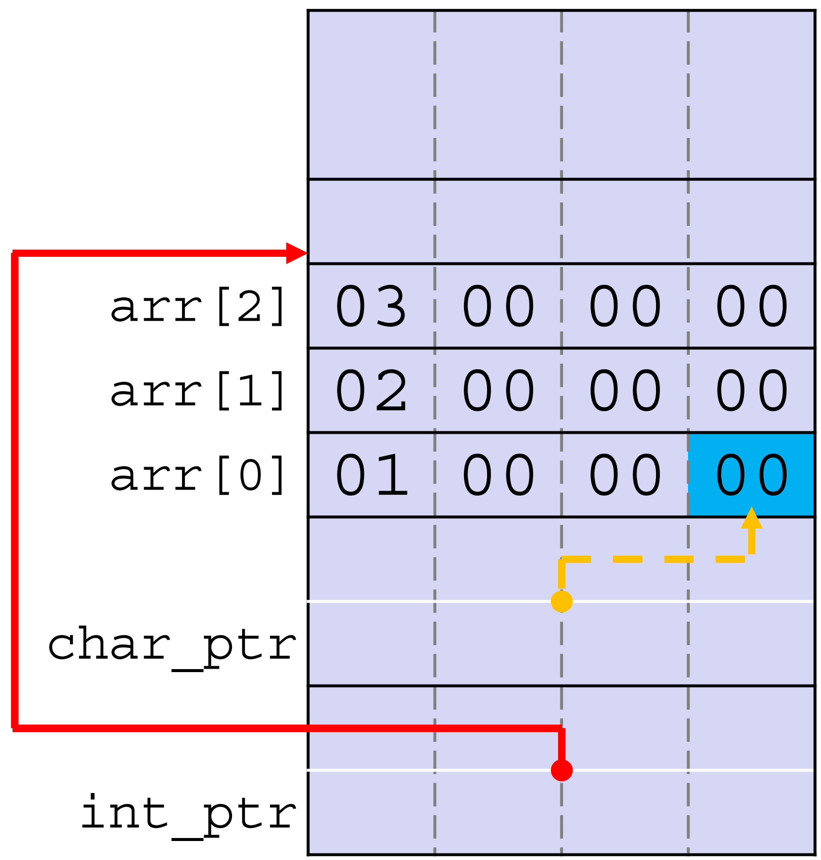
pointerarithmetic.c

Stack
(assume x86-64)



char_ptr: 0x0x7fffffde013

***char_ptr:** 0

Lecture Outline

- Pointer Arithmetic
- **Pointers as Parameters**
- Pointers and Arrays
- Function Pointers
- Heap-allocated Memory

C is Call-By-Value

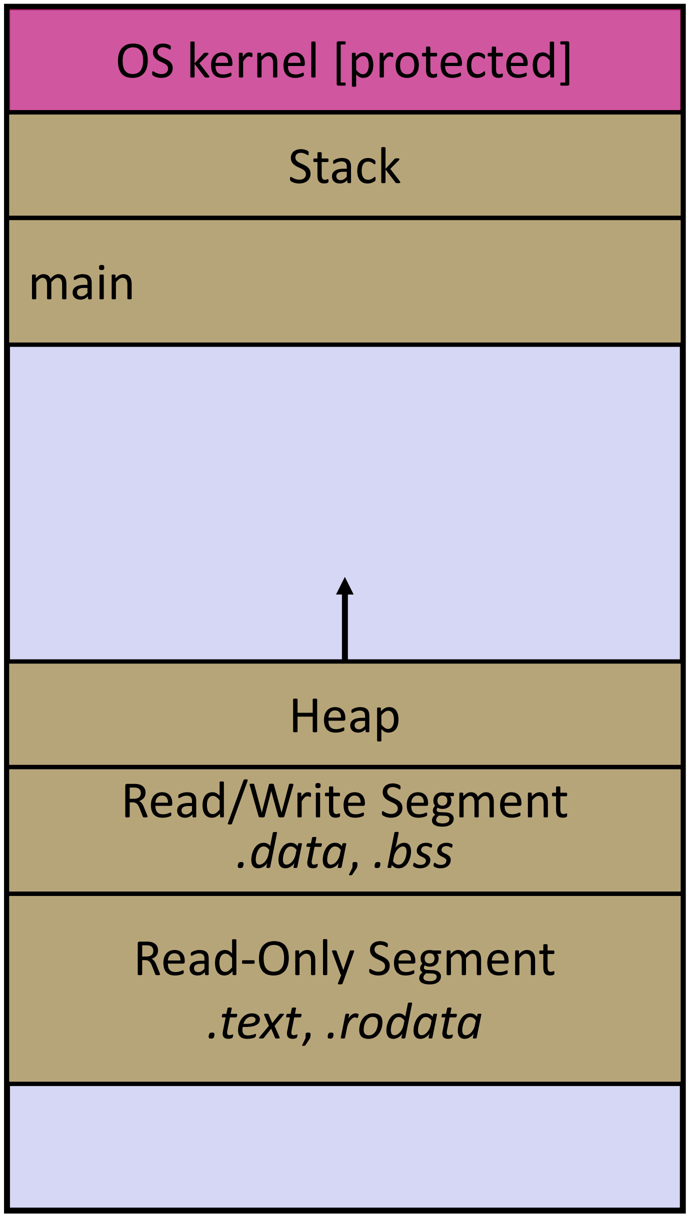
- C (and Java) pass arguments by *value*
  - Callee receives a **local copy** of the argument
    - Register or Stack
  - If the callee modifies a parameter, the caller's copy *isn't* modified

```
void swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

int main(int argc, char** argv) {
  int a = 42, b = -7;
  swap(a, b);
  ...
```

Broken Swap

Note: Arrow points to *next* instruction.



brokenswap.c

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void swap(int a, int b) {
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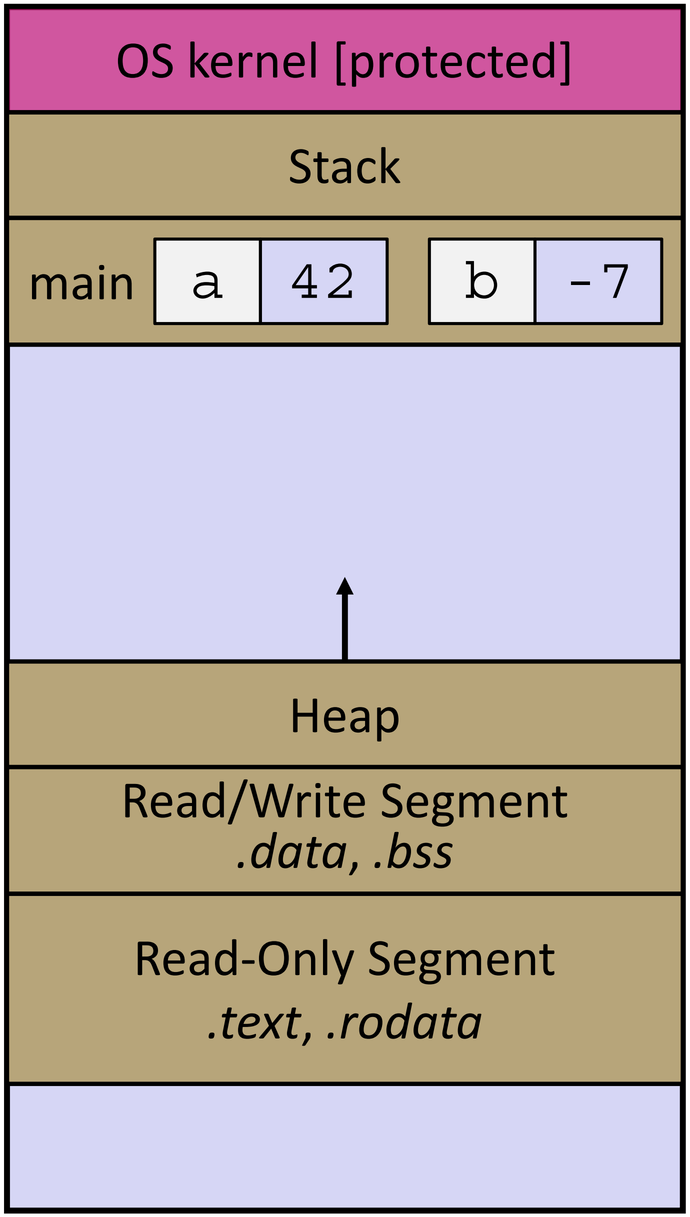

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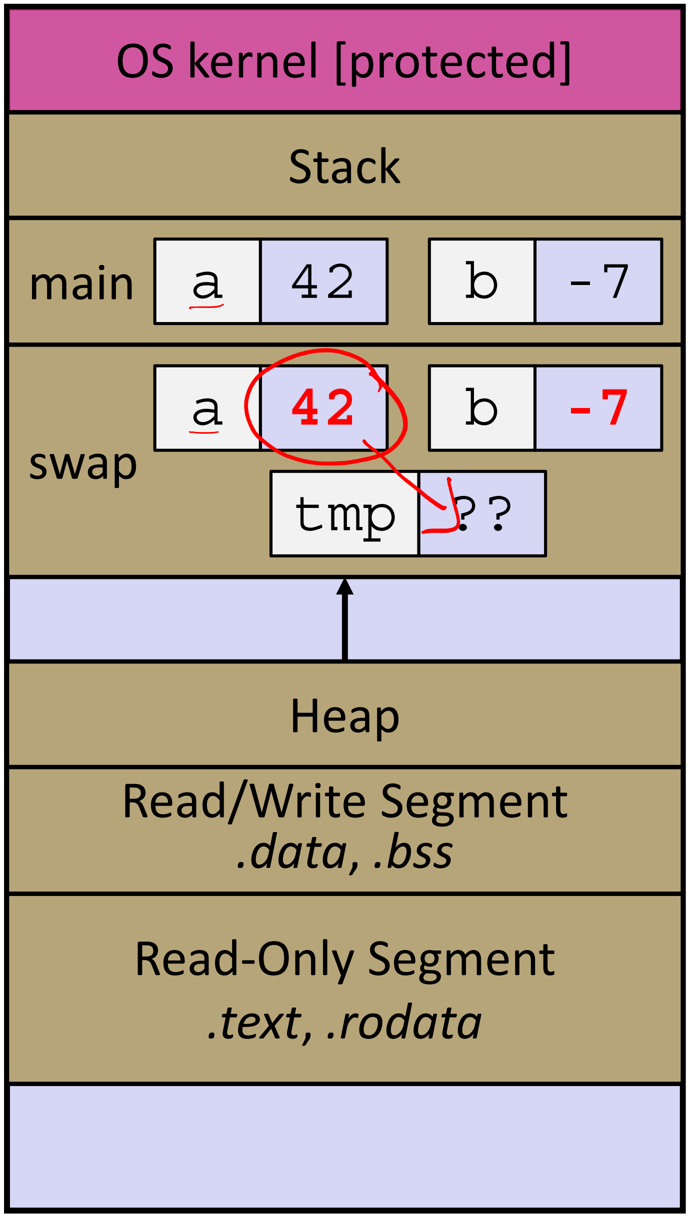

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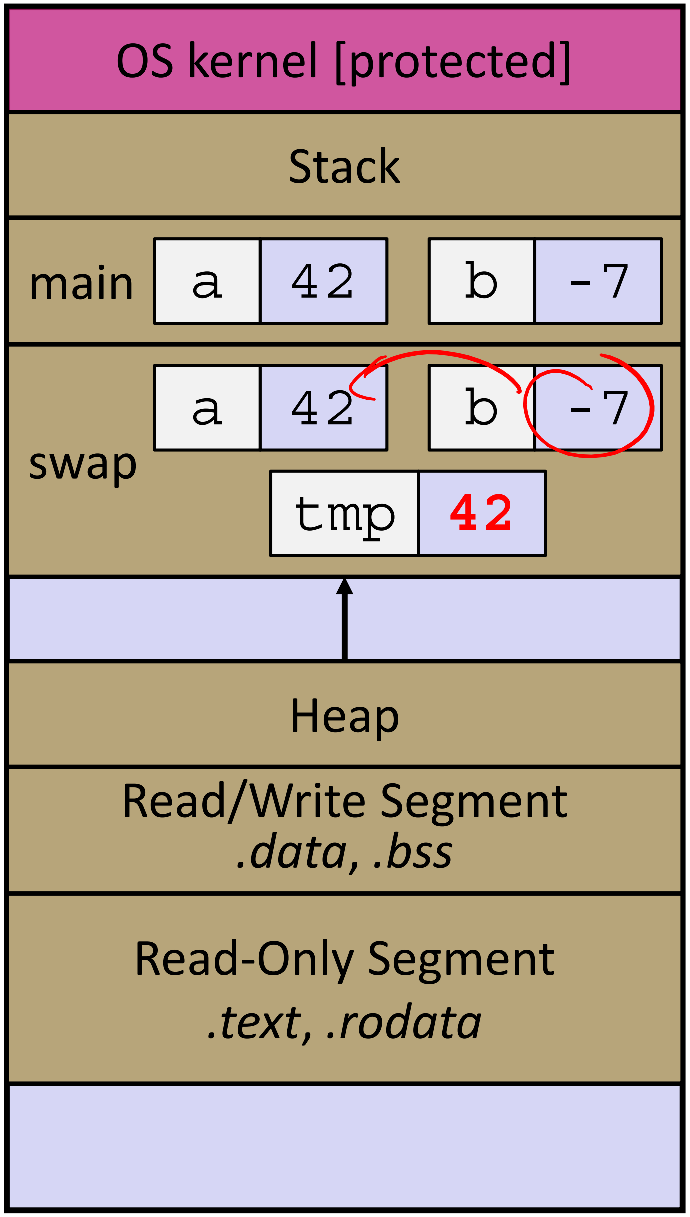

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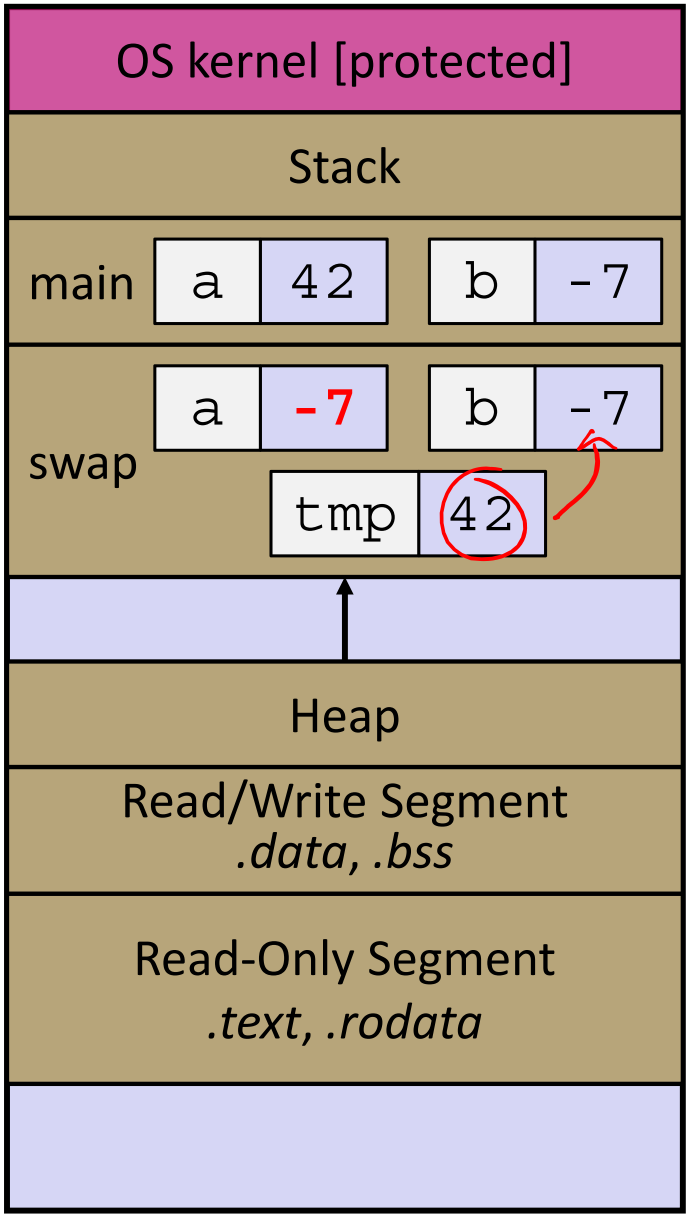

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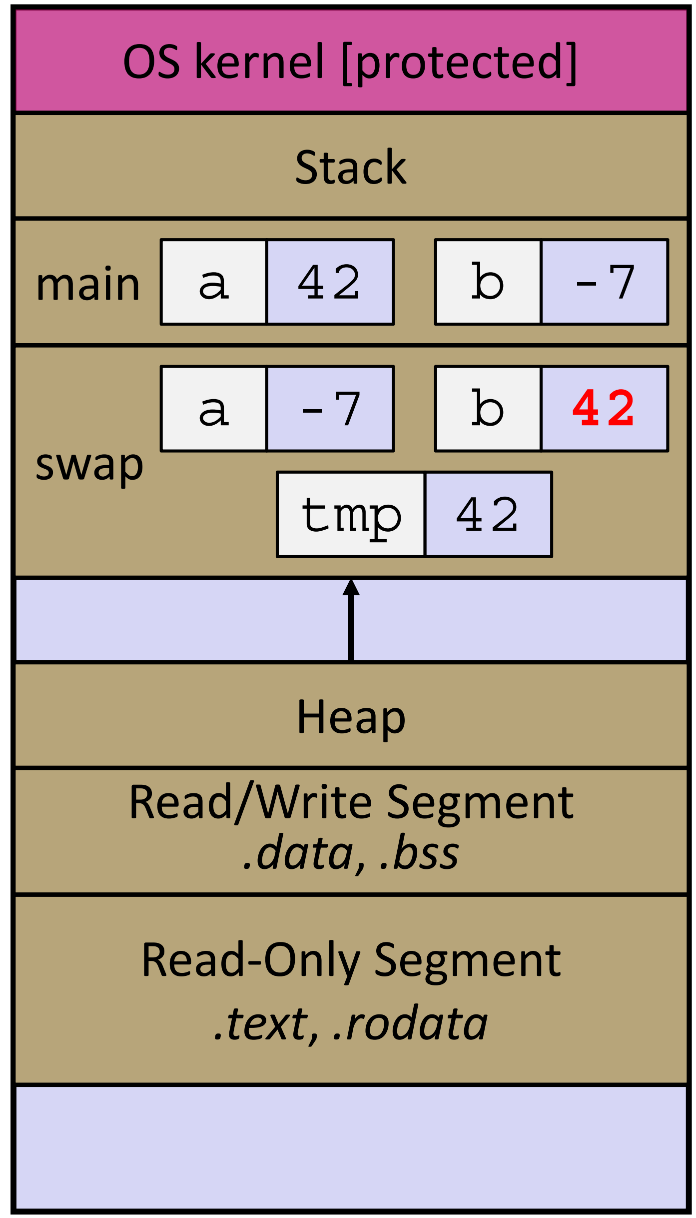

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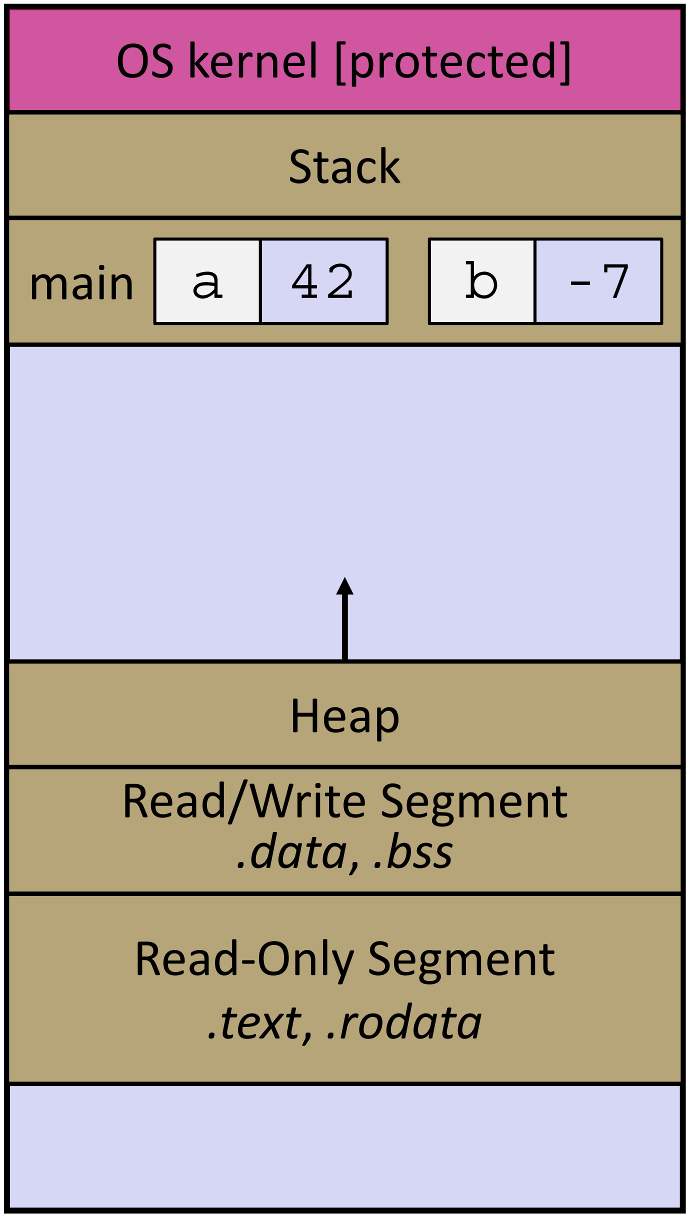

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  ...
```

Faking Call-By-Reference in C

- Can use pointers to *approximate* call-by-reference
  - Callee still receives a **copy** of the pointer (*i.e.* call-by-value), but it can modify something in the caller's scope by dereferencing the pointer parameter

aptr bptr

```
void swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

int main(int argc, char** argv) {
  int a = 42, b = -7;
  swap(&a, &b);
  ...
```

Fixed Swap

Note: Arrow points to *next* instruction.

swap.c

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void swap(int* a, int* b) {
  int tmp = *a;
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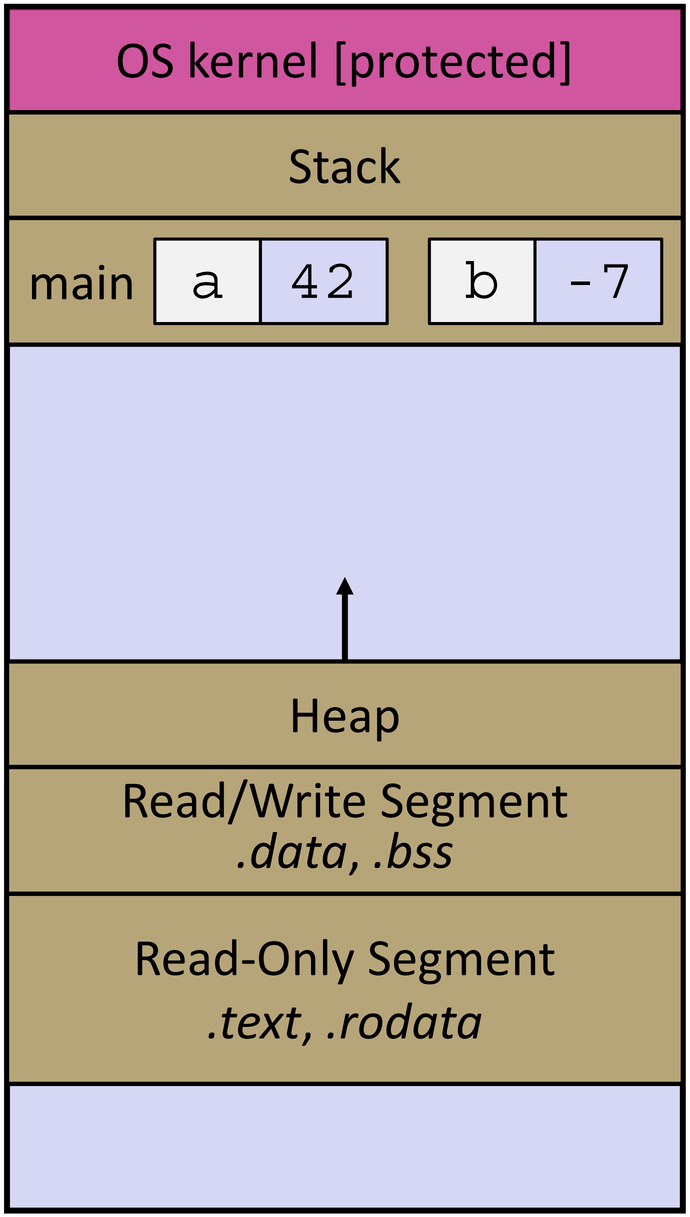

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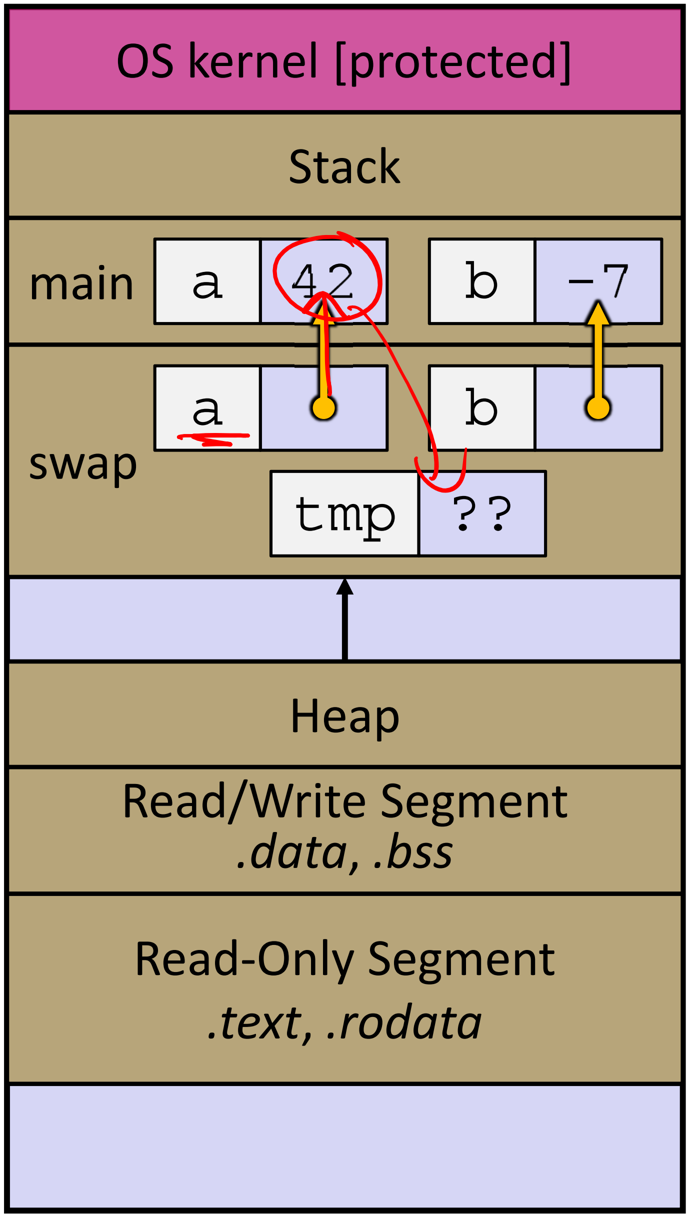
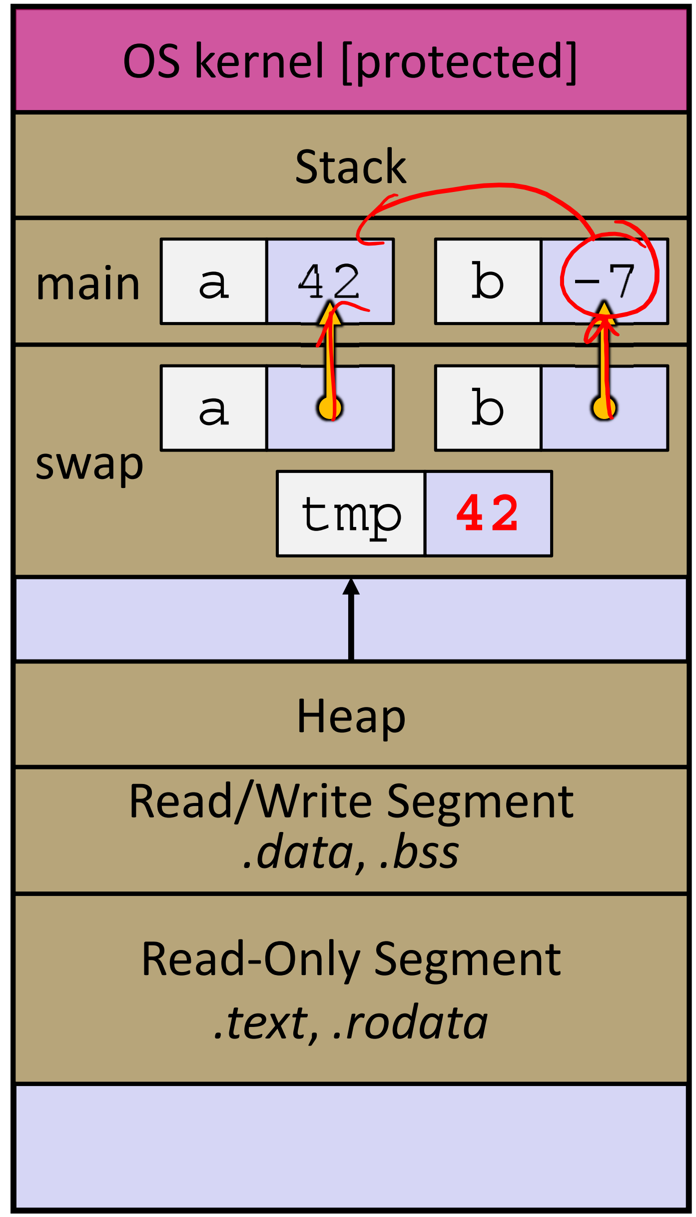


Fixed Swap



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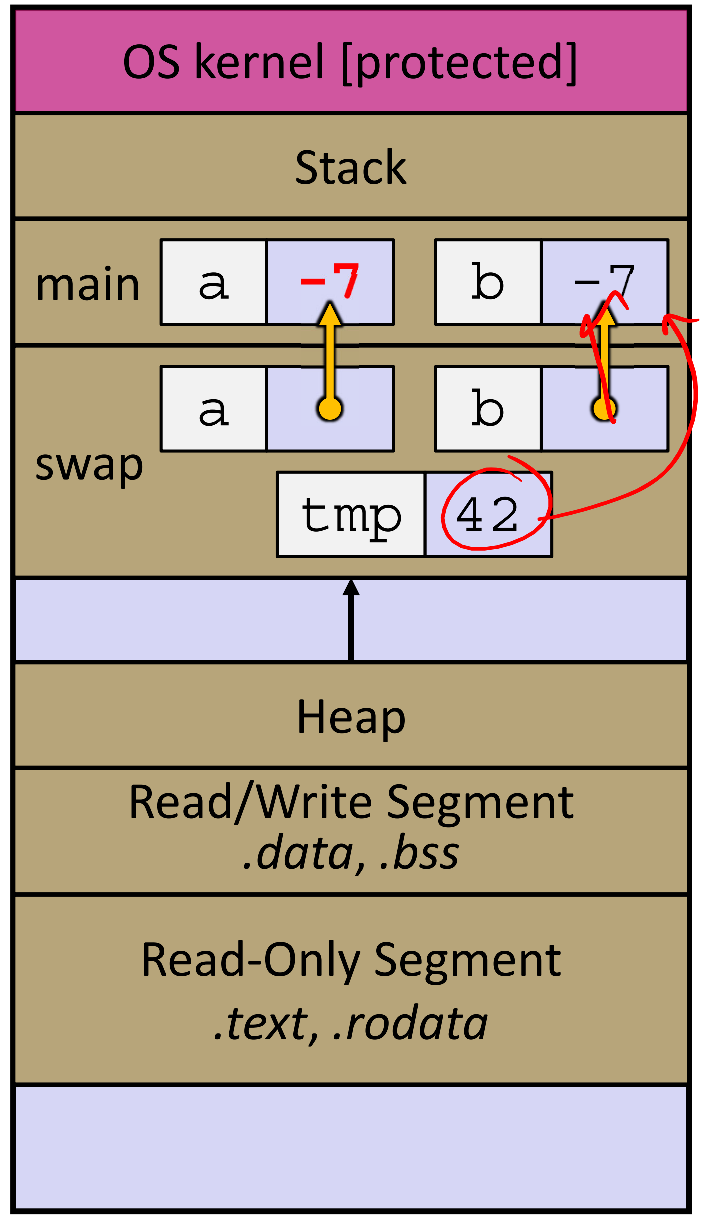
Fixed Swap



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Fixed Swap

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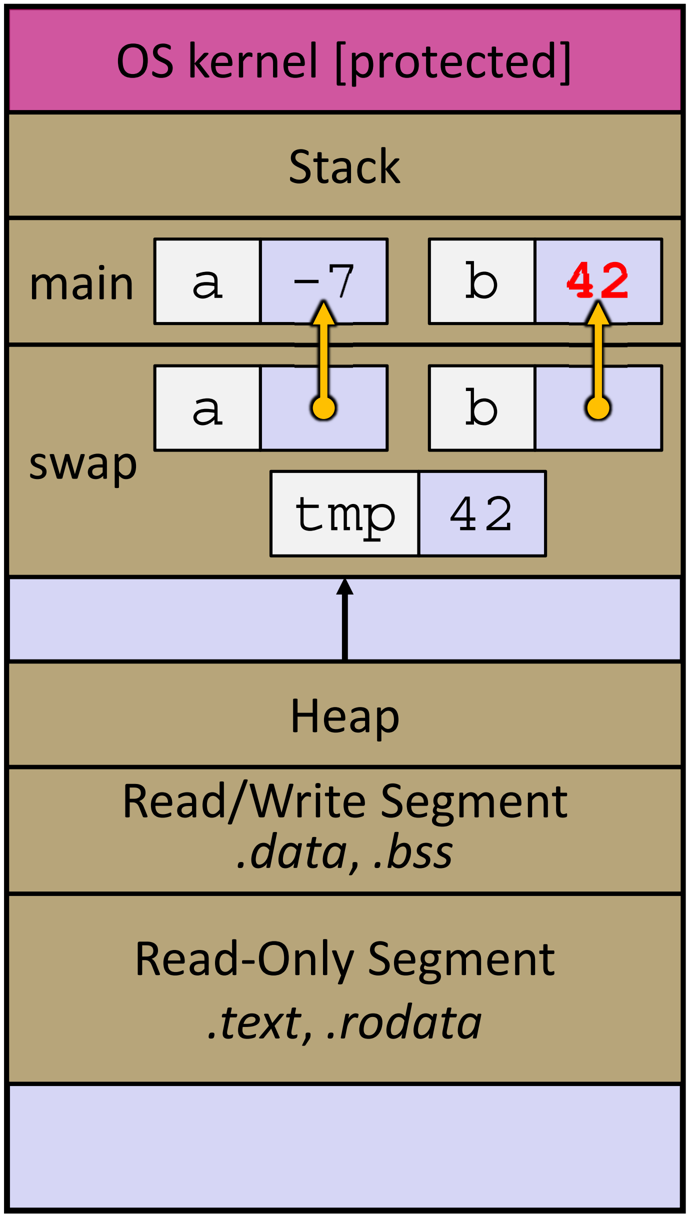

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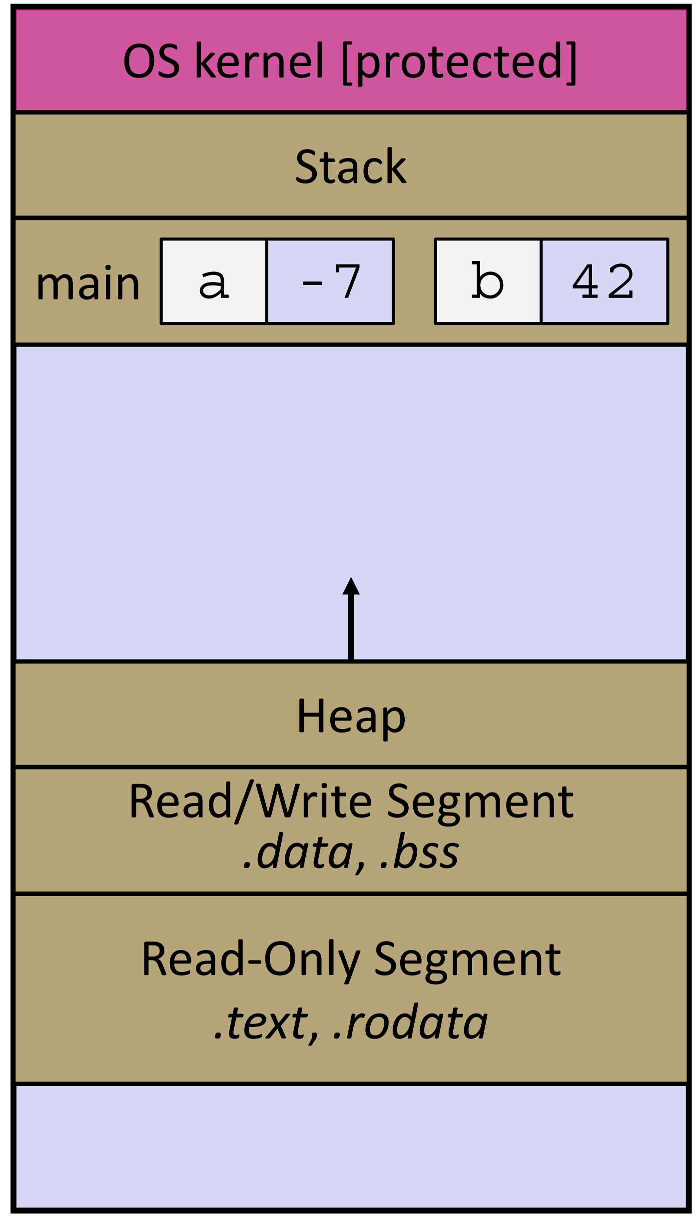


Lecture Outline

- Pointer Arithmetic
- Pointers as Parameters
- **Pointers and Arrays**
- Function Pointers
- Heap-allocated Memory

Pointers and Arrays

- A pointer can point to an array element
  - You can use array indexing notation on pointers
    - `ptr[i]` is `*(ptr+i)` with pointer arithmetic – reference the data `i` elements forward from `ptr`
  - An array name's value is the beginning address of the array
    - *Like* a pointer to the first element of array, but can't change

```
int a[] = {10, 20, 30, 40, 50};
int* p1 = &a[3];  // refers to a's 4th element
int* p2 = &a[0];  // refers to a's 1st element
int* p3 = a;      // refers to a's 1st element

*p1 = 100;
*p2 = 200;
p1[1] = 300;
p2[1] = 400;
p3[2] = 500;      // final: 200, 400, 500, 100, 300
```

STYLE TIP

Array Parameters

- Array parameters are *actually* passed as pointers to the first array element
  - The `[]` syntax for parameter types is just for convenience
    - OK to use whichever best helps the reader

This code:

```
void f(int a[]);
                pointer
int main( ... ) {
  int a[5];
           array
  ...
  f(a);
  return EXIT_SUCCESS;
}

void f(int a[]) {
```

Equivalent to:

```
void f(int* a);

int main( ... ) {
  int a[5];
  ...
  f(&a[0]);
  return EXIT_SUCCESS;
}

void f(int* a) {
```

Lecture Outline

- Pointers & Pointer Arithmetic
- Pointers as Parameters
- Pointers and Arrays
- **Function Pointers**
- Heap-allocated Memory

Function Pointers

jmp foo $\xrightarrow{\text{address}}$ 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);
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

Lecture Outline

- Pointers & Pointer Arithmetic
- Pointers as Parameters
- Pointers and Arrays
- Function Pointers
- **Heap-allocated Memory**

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;
}
```

```
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 fixed size for Linux x86-64
  - We need memory whose size is not known in advance to the caller (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 explicitly deallocated 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

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()`

malloc returns void*, but good practice to explicitly cast

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

always check for NULL!

calloc()

watch out! different parameters

- 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
```

free()

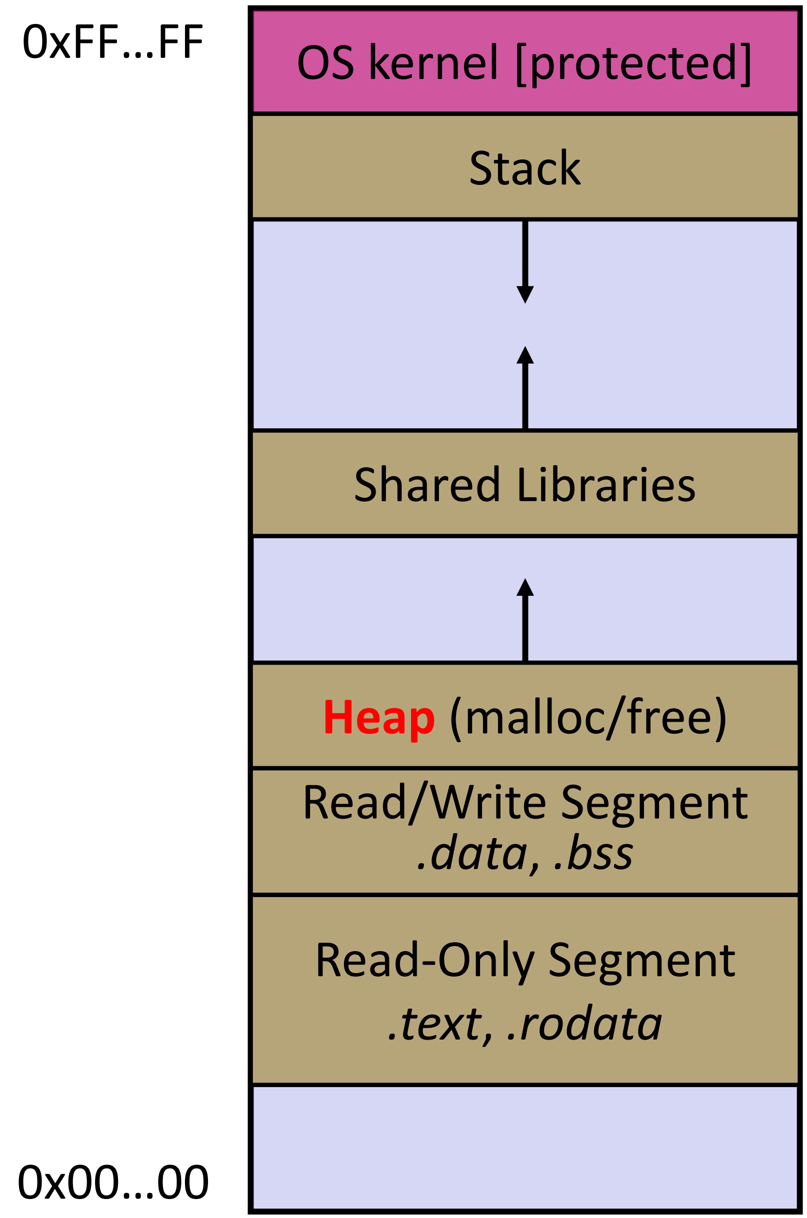
- Usage: `free(pointer);`
- Deallocates the memory pointed-to by the pointer
  - Pointer *must* point to the first byte of heap-allocated memory (*i.e.* something previously returned by **malloc** or **calloc**)
  - Freed memory becomes eligible for future allocation
  - Pointer is unaffected by call 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
```

(debugging/non-performance critical code only)

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

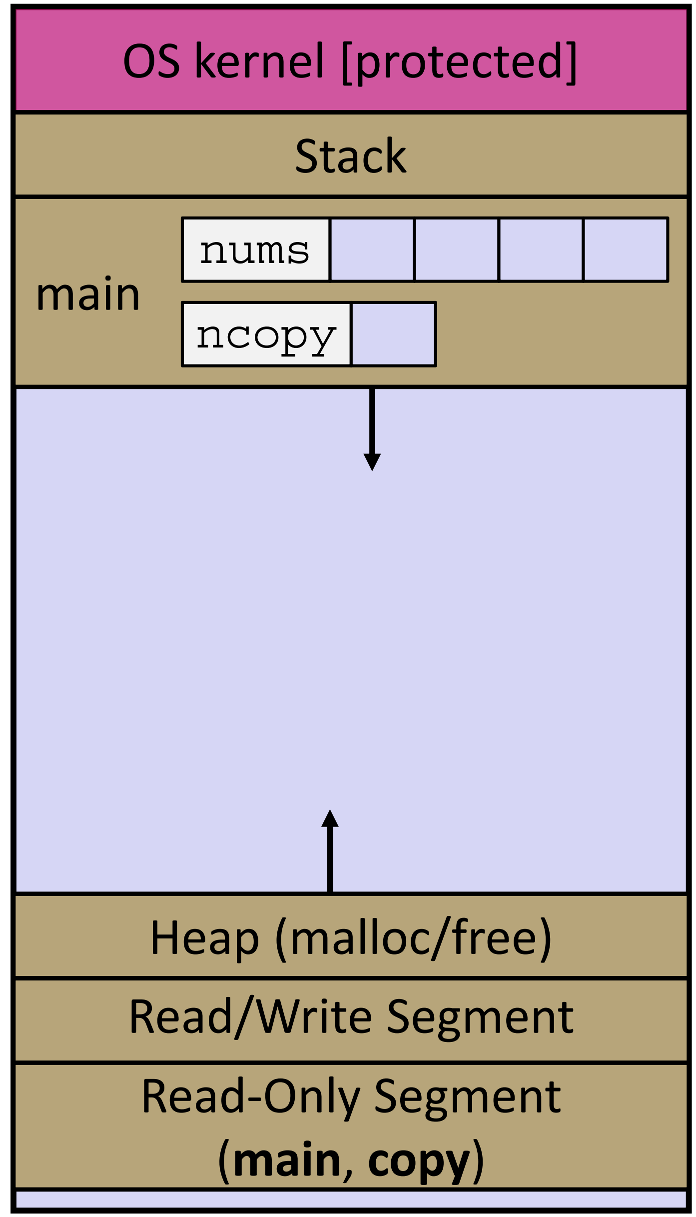
```
#include <stdlib.h>

int* copy(int a[], int size) {
  int i, *a2;
                  should be (int*) here
  a2 = malloc(size*sizeof(int));
  if (a2 == NULL)
    return NULL;

  for (i = 0; i < size; i++)
    a2[i] = a[i];

  return a2;
}

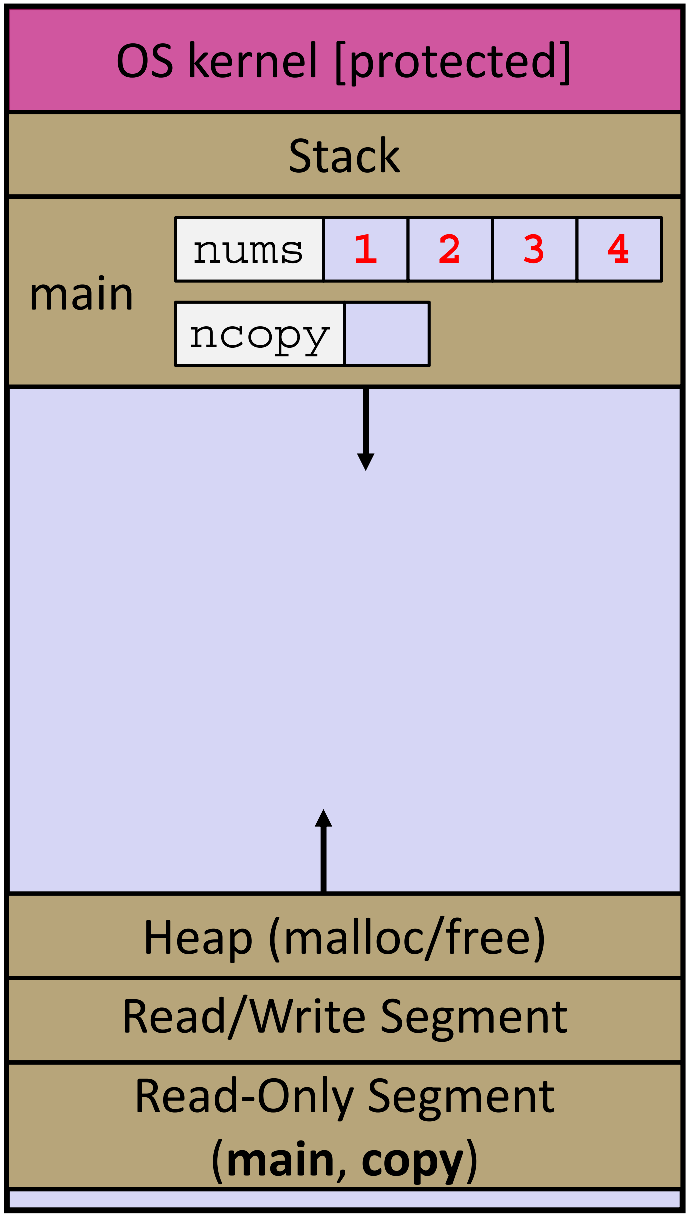
int main(int argc, char** argv) {
  int nums[4] = {1, 2, 3, 4};
  int* ncopy = copy(nums, 4);
  // .. do stuff with the array ..
  free(ncopy);
  return EXIT_SUCCESS;
}
```



Heap and Stack Example

arraycopy.c

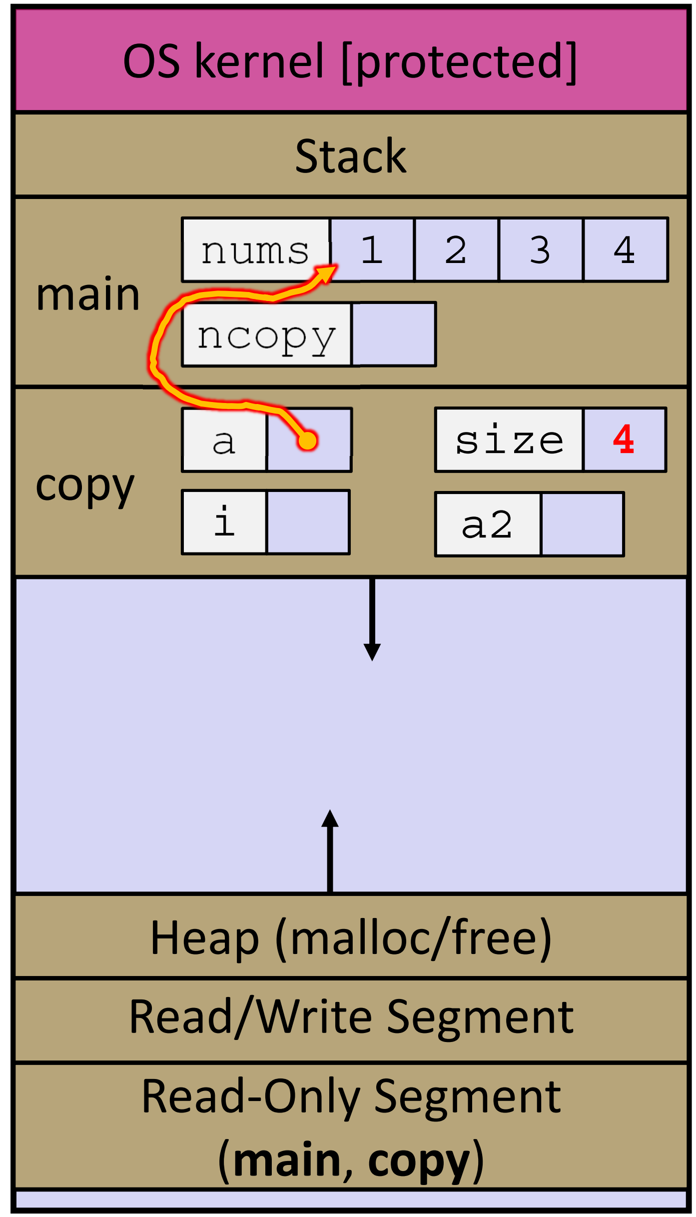
```c
#include <stdlib.h>

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

arraycopy.c

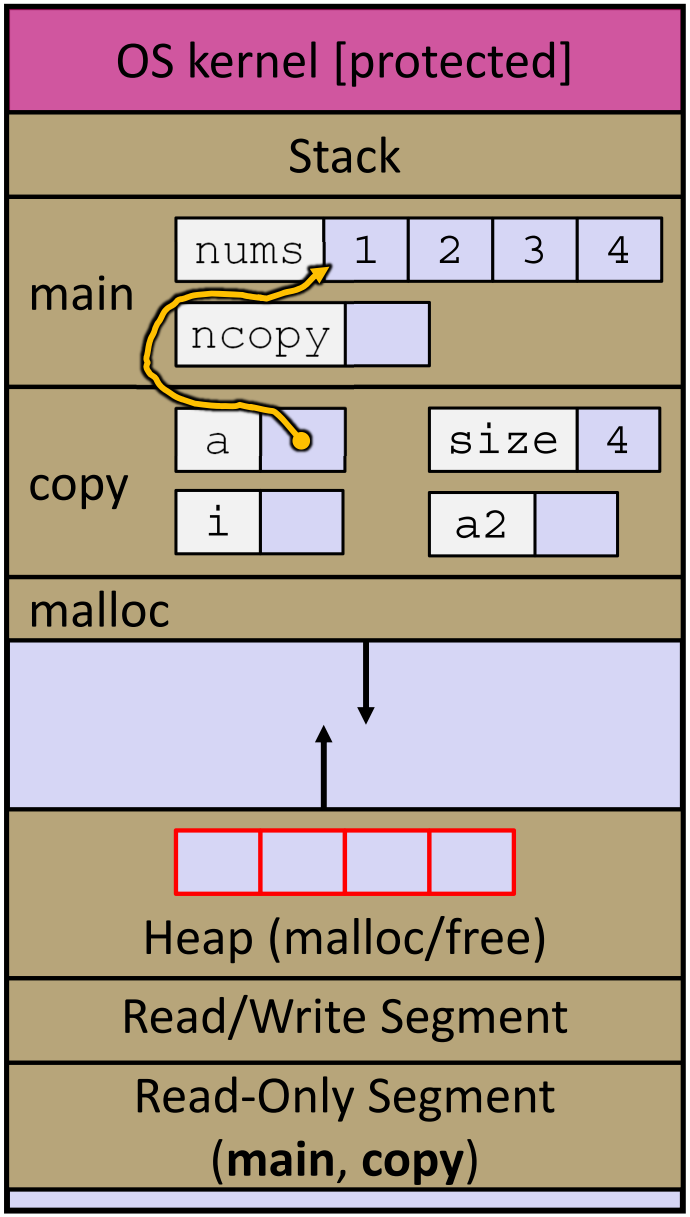
```
#include <stdlib.h>
                        actually a  int*
int* copy(int a[], int size) {
  int i, *a2;
                 4          4
  a2 = malloc(size*sizeof(int));
  if (a2 == NULL)
    return NULL;

  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

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;
}
```

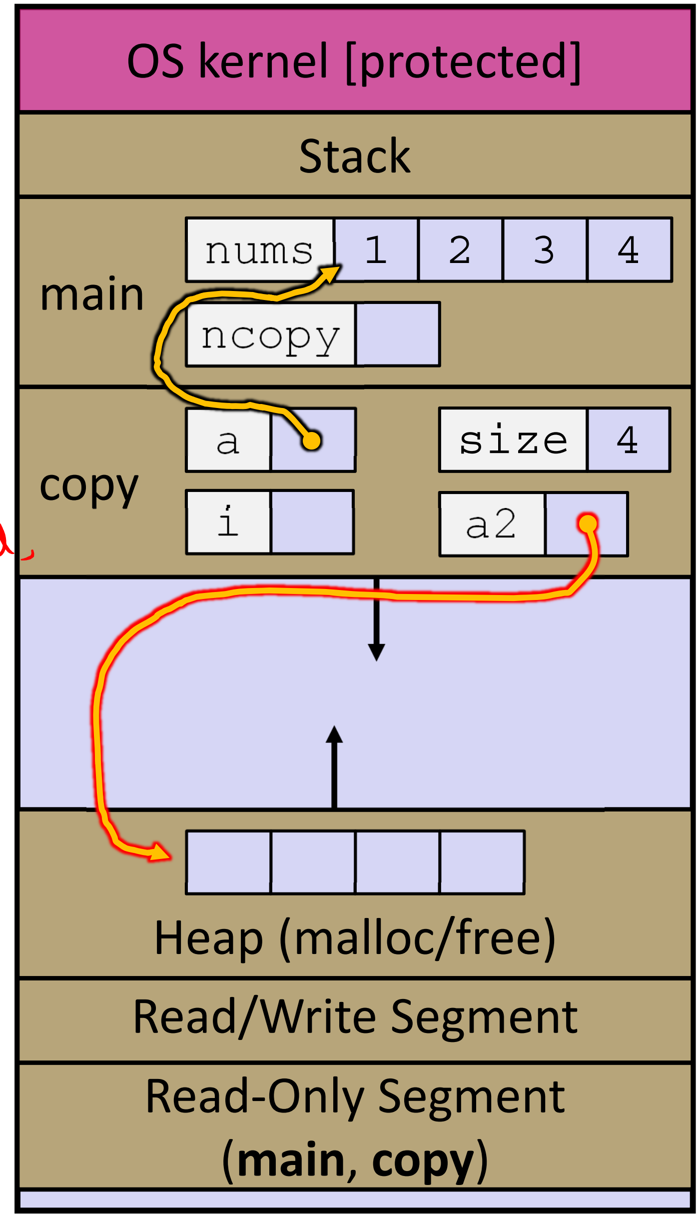


Heap and Stack Example

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;
}
```

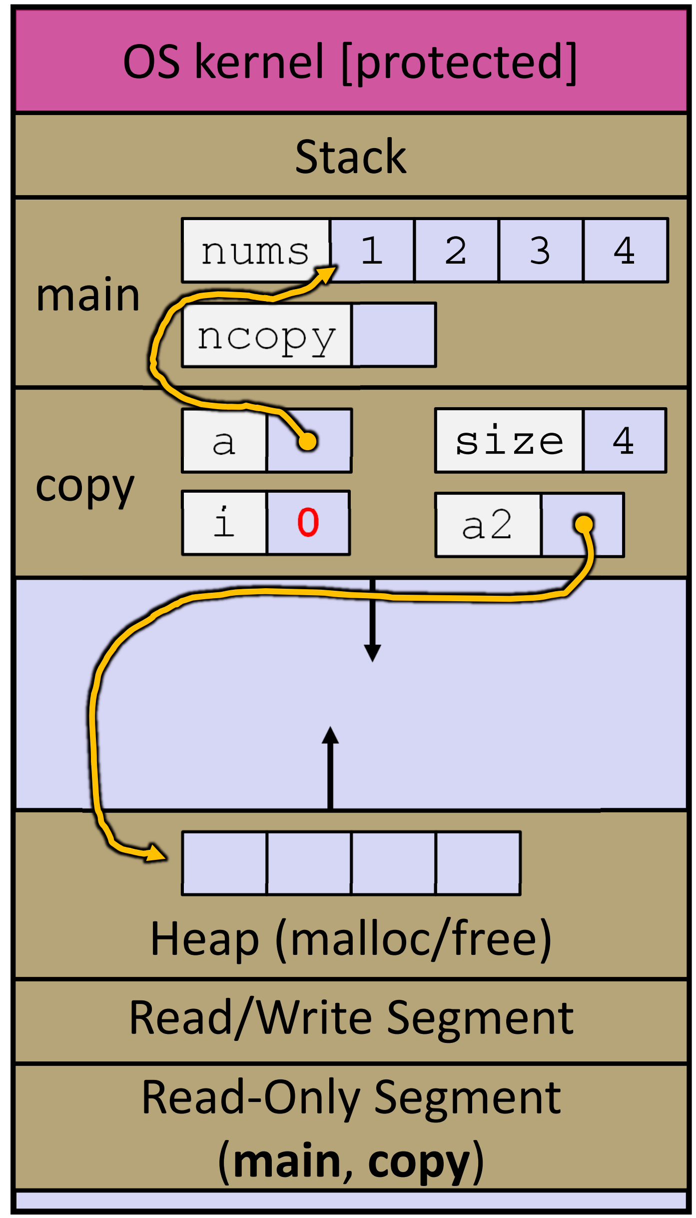
if succeeded, otherwise NULL



Heap and Stack Example

arraycopy.c

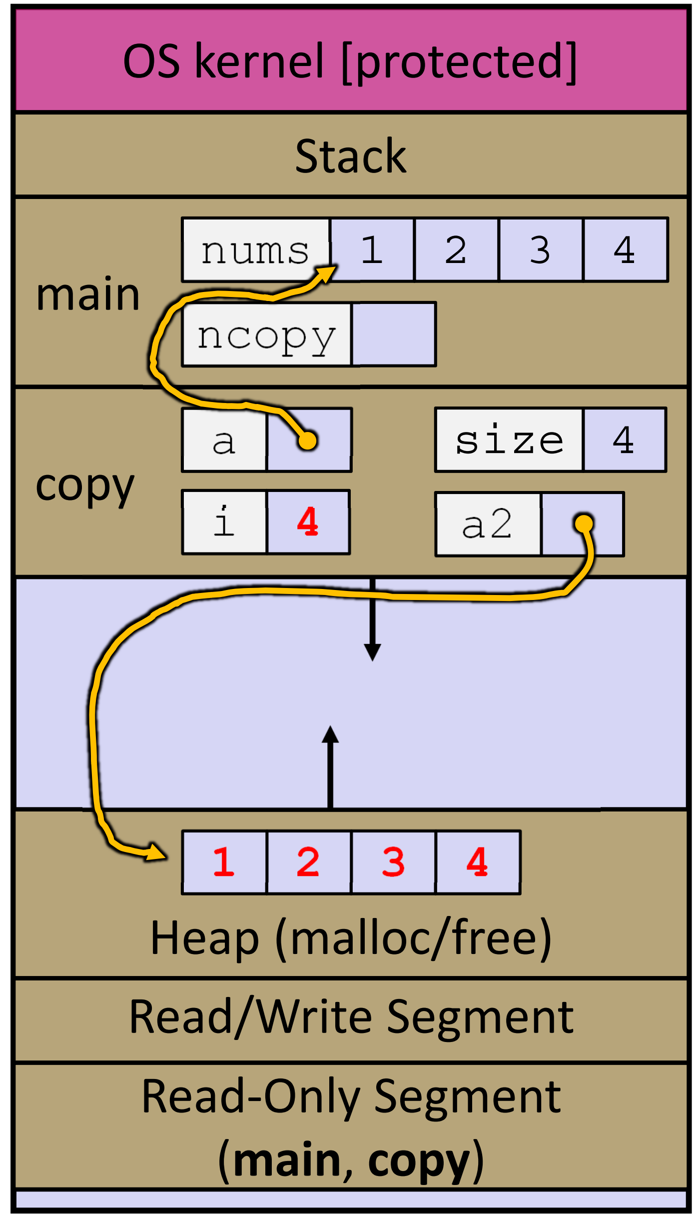
```
#include <stdlib.h>

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

arraycopy.c

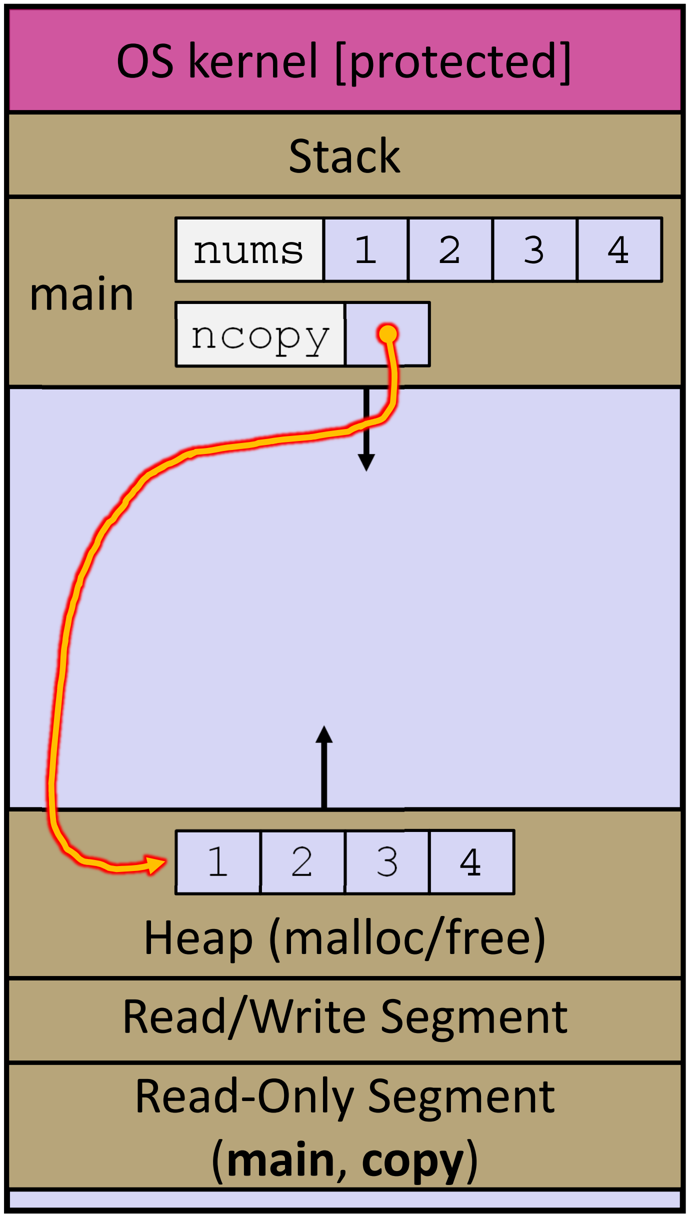
```
#include <stdlib.h>

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

arraycopy.c

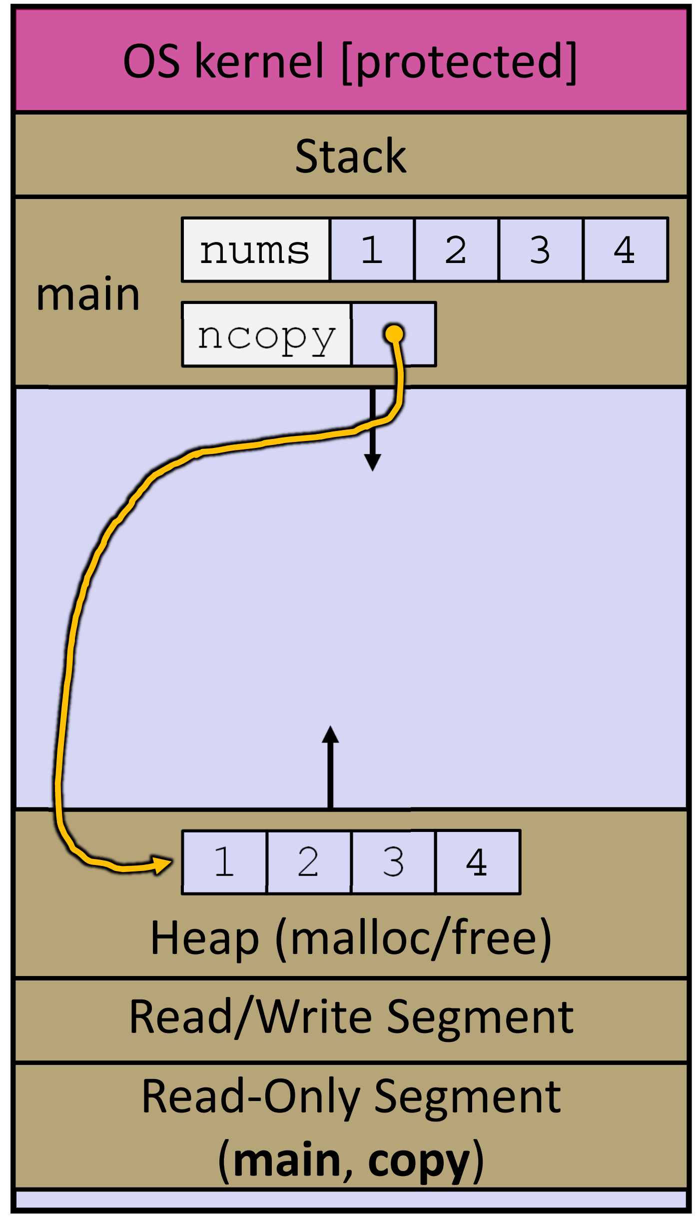
```
#include <stdlib.h>

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

arraycopy.c

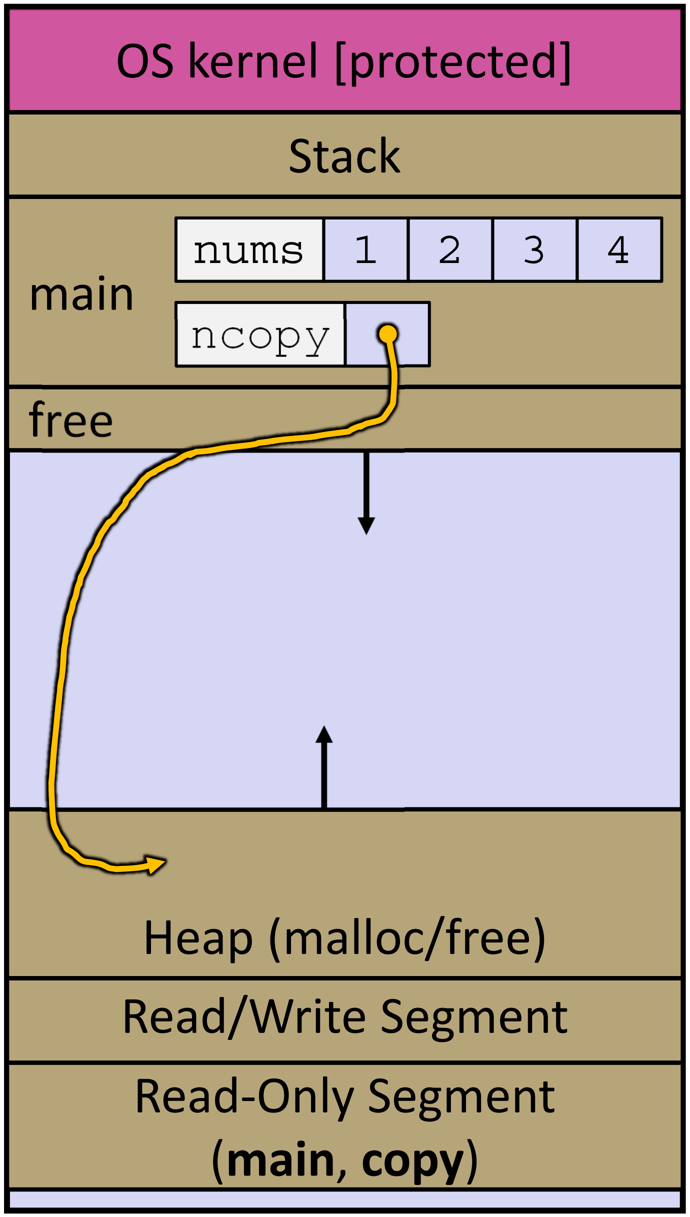
```
#include <stdlib.h>

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

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;
}
```

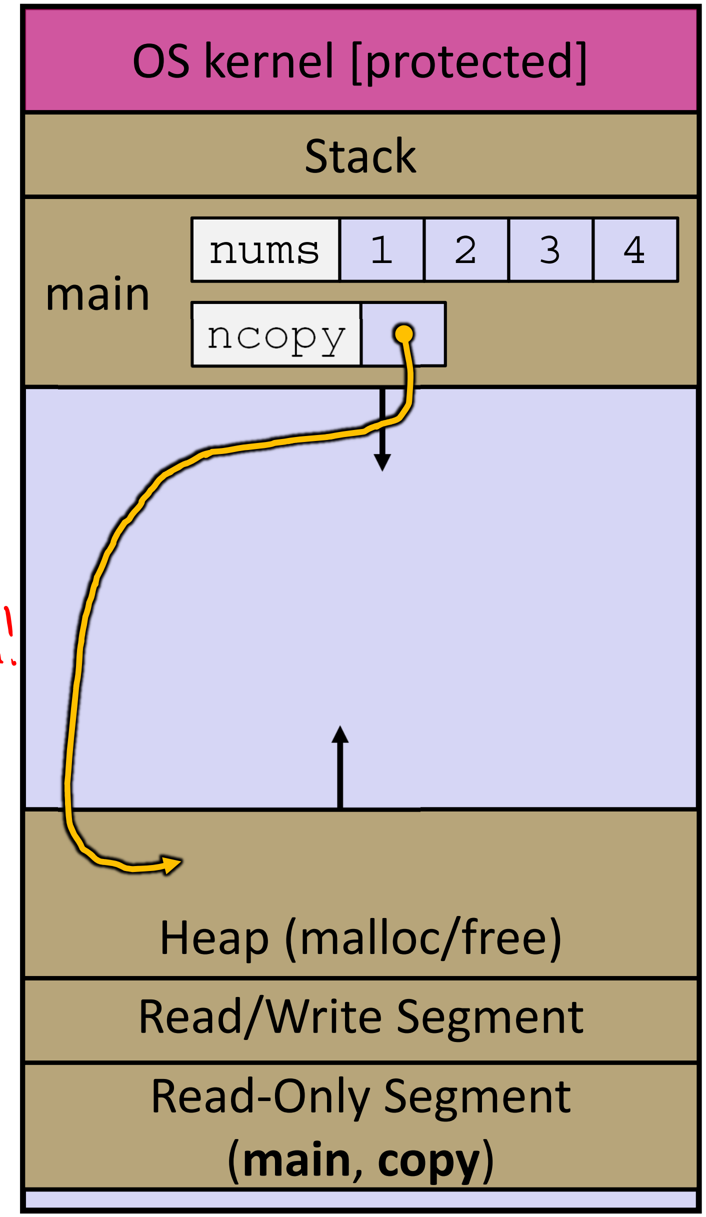


Heap and Stack Example

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!



Extra Exercise #1

- Use a box-and-arrow diagram for the following program and explain what it prints out:

```
#include <stdio.h>

int foo(int* bar, int** baz) {
  *bar = 5;
  *(bar+1) = 6;
  *baz = bar + 2;
  return *((*baz)+1);
}

int main(int argc, char** argv) {
  int arr[4] = {1, 2, 3, 4};
  int* ptr;

  arr[0] = foo(&arr[0], &ptr);
  printf("%d %d %d %d %d\n",
         arr[0], arr[1], arr[2], arr[3], *ptr);
  return 0;
}
```

Extra Exercise #2

- Write a program that determines and prints out whether the computer it is running on is little-endian or big-endian.
  - Hint: `pointerarithmetic.c` from today's lecture or `show_bytes.c` from 351

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

Extra Exercise #4

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