Pointers, Pointers, Pointers …

CSE 333 Autumn 2019

Instructor: Hannah C. Tang

Teaching Assistants:

Dao Yi	Farrell Fileas	Lukas Joswiak
Nathan Lipiarski	Renshu Gu	Travis McGaha
Yibo Cao	Yifan Bai	Yifan Xu

"Pointers are merely variables that contain memory addresses"

Poll Everywhere

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About how long did Exercise 1 take?

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

Administrivia (1 of 2)

- Exercise 2 out today and due Wednesday 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

Administrivia (2 of 2)

- Homework 0 due TONIGHT
  - Logistics and infrastructure for projects
    - `clint` and `valgrind` are useful for exercises, too

- Homework 1 already out, due in 2 weeks (Thu 10/10)
  - Linked list and hash table implementations in C
  - Get starter code using `git pull` in your course repo
    - Might have a merge if your local copy has unpushed changes
    - If git drops you into vim, `:q` to quit or `:wq` if you want to save changes

Lecture Outline

- **Pointers & Pointer Arithmetic**
- Pointers as Parameters
- Pointers and Arrays
- Function Pointers

"Pointers are merely variables that contain memory addresses"

Box-and-Arrow Diagrams

boxarrow.c

```
int main(int argc, char **argv) {
  int32_t x = 1;
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return 0;
}
```

address	**name**	value

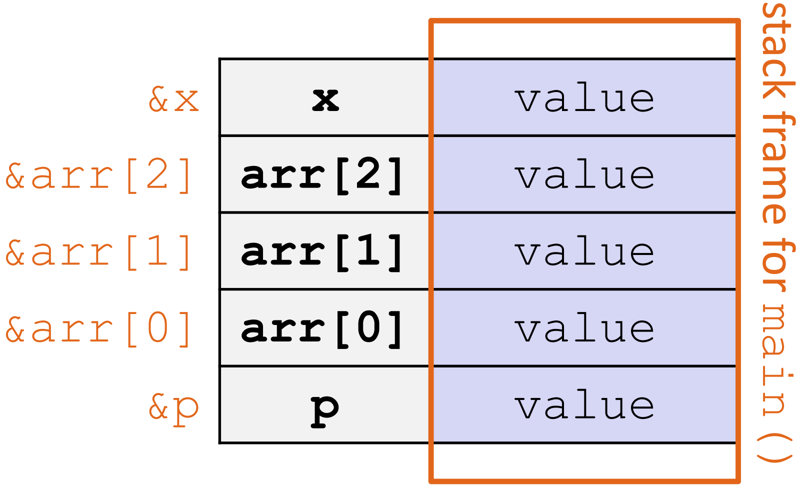
Box-and-Arrow Diagrams

boxarrow.c

```
int main(int argc, char **argv) {
  int32_t x = 1;
  int32_t arr[3] = {2, 3, 4};
  int32_t *  = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return 0;
}
```



Box-and-Arrow Diagrams

boxarrow.c

```
int main(int argc, char **argv) {
  int32_t x = 1;
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return 0;
}
```

address	name	value
&x	**x**	1
&arr[2]	**arr[2]**	4
&arr[1]	**arr[1]**	3
&arr[0]	**arr[0]**	2
&p	**p**	&arr[1]

Box-and-Arrow Diagrams

boxarrow.c

```c
int main(int argc, char **argv) {
  int32_t x = 1;
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return 0;
}
```

address	name	value

address	name	value
0x7fff…dc	x	1
0x7fff…d8	arr[2]	4
0x7fff…d4	arr[1]	3
0x7fff…d0	arr[0]	2
0x7fff…c8	p	0x7fff…d4

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)`
  - Works nicely for arrays
  - Does not work on `void*`, since `void` doesn't have a size!
- Valid pointer arithmetic:
  - Add/subtract an integer to/from a pointer
  - Subtract two pointers (within stack frame or malloc block)
  - Compare pointers (`<`, `<=`, `==`, `!=`, `>`, `>=`), including `NULL`
  - … plenty of valid-but-inadvisable operations, too!

Inadvisable Pointer Examples 😱

```
// Leave them uninitialized!
int *int_ptr;
*int_ptr = 333;
```

```
// Use garbage values!
int *int_ptr = rand();
*int_ptr = 333;
```

```
// Reinterpret raw bytes!
double d = 3.14;
int *int_ptr = (int *) &d;
*int_ptr = 333;
```

inadvisable_pointers.c

"Pointers are merely variables that contain memory addresses"

Inadvisable Pointer-Specific Examples

```
// Uninitialized!
int ***ipp;
***ipp = 333;

// Garbage values!
ipp = rand();
***ipp = 333;

// Reinterpret raw bytes!
double d = 3.14;
double *dp = &d;
ipp = (int **) &dp;
*ip = 333;
```

```
void *vp = (void*) ip;
void **vpp = &vp;

vpp = vp; // lol typechecking
```

inadvisable_pointers.c

"Since pointers are variables, we can do all these things recursively!"

Poll Everywhere

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```
int main(int argc, char **argv) {
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];
  int32_t **dp = &p;  // pointer to a pointer

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

  return 0;
}
```

At this point in the code (after the final `*(*dp) += 1;`), what values are stored in `arr[]`?

address	name	value
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. I'm not sure …

PollEverywhere Solution

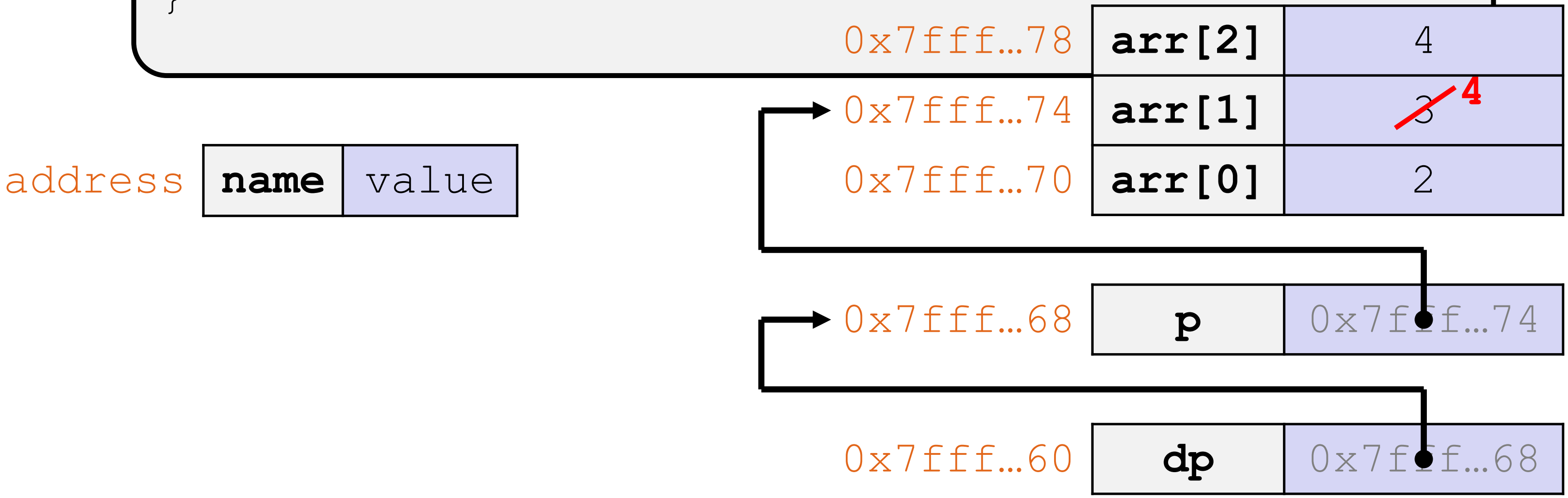
Note: arrow points to *next* instruction to be executed.

boxarrow2.c

```
int main(int argc, char **argv) {
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];
  int32_t **dp = &p;  // pointer to a pointer

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

  return 0;
}
```



PollEverywhere Solution

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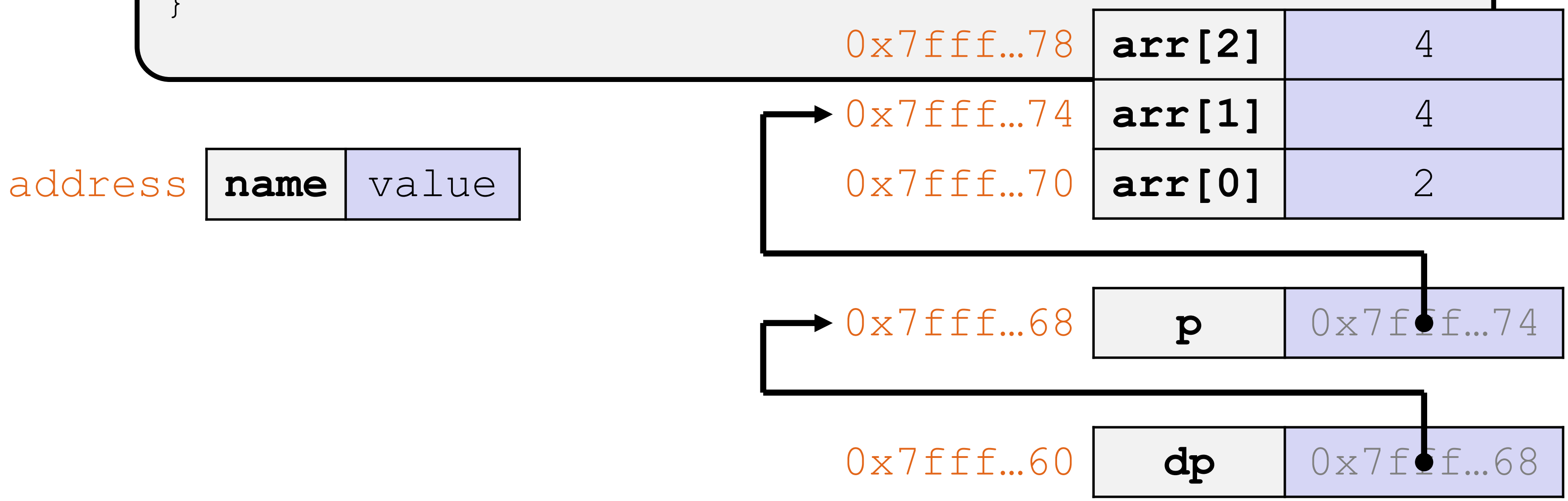
boxarrow2.c

```
int main(int argc, char **argv) {
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];
  int32_t **dp = &p;  // pointer to a pointer

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

  return 0;
}
```



PollEverywhere Solution

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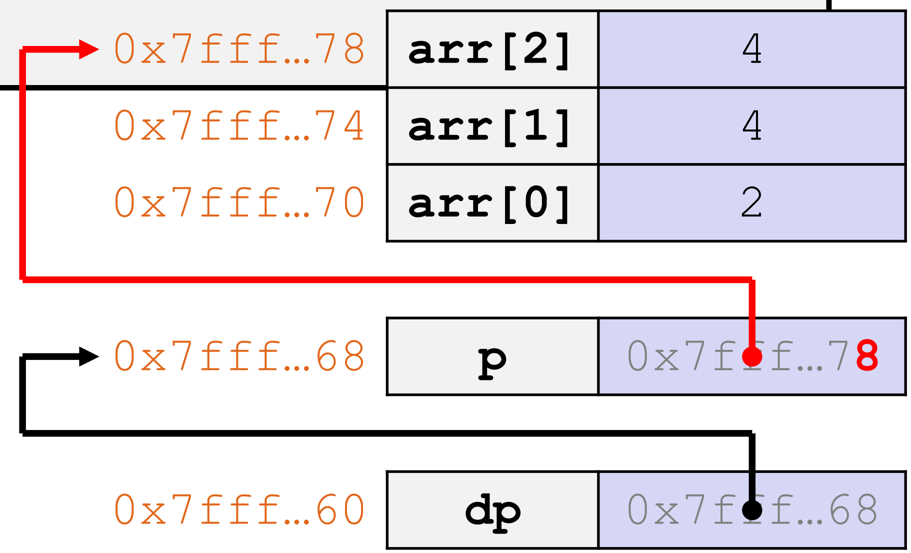
boxarrow2.c

```
int main(int argc, char **argv) {
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];
  int32_t **dp = &p;  // pointer to a pointer

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

  return 0;
}
```

address	name	value



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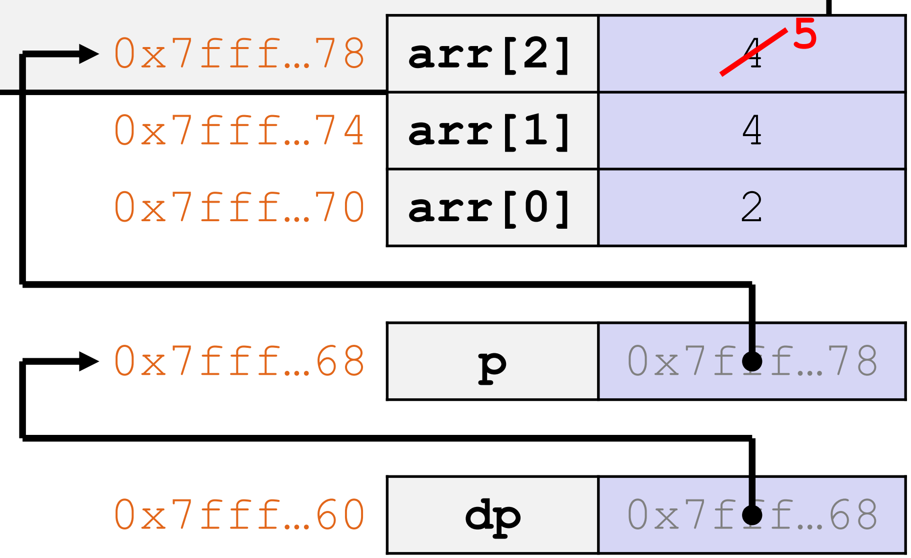
boxarrow2.c

```
int main(int argc, char **argv) {
  int32_t arr[3] = {2, 3, 4};
  int32_t *p = &arr[1];
  int32_t **dp = &p;  // pointer to a pointer

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

  return 0;
}
```

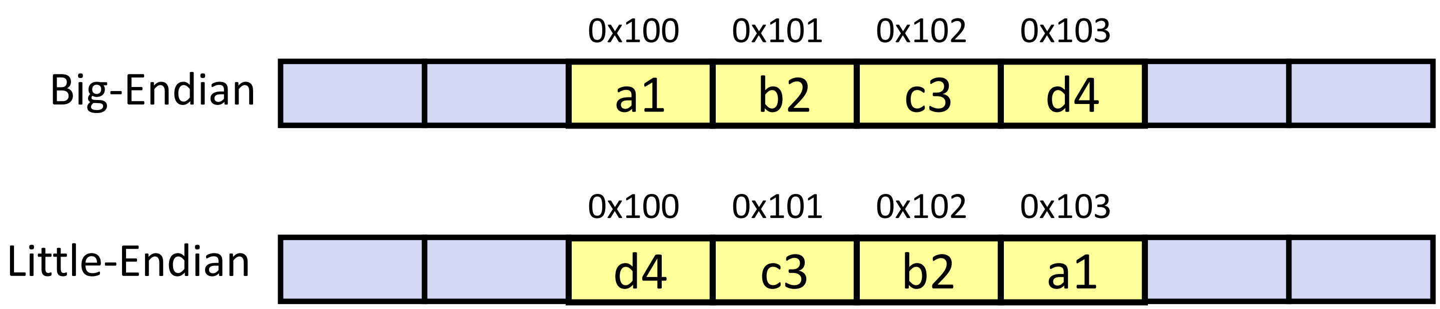
address	name	value



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

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

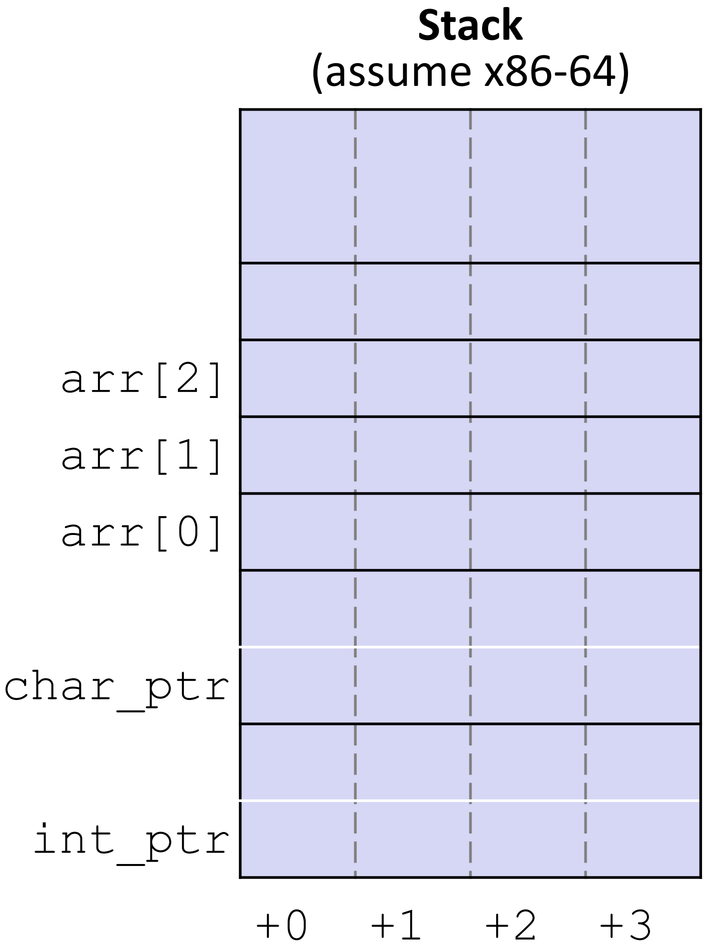


Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
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 0;
}
```

pointerarithmetic.c

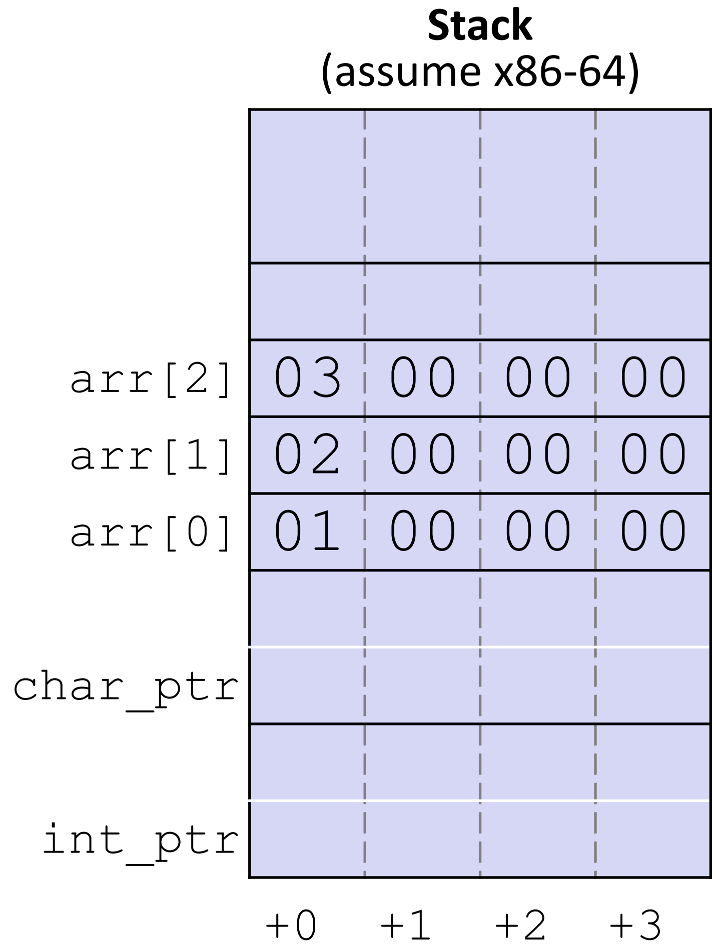


Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

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

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

  char_ptr += 1;
  char_ptr += 2;

  return 0;
}
```

pointerarithmetic.c

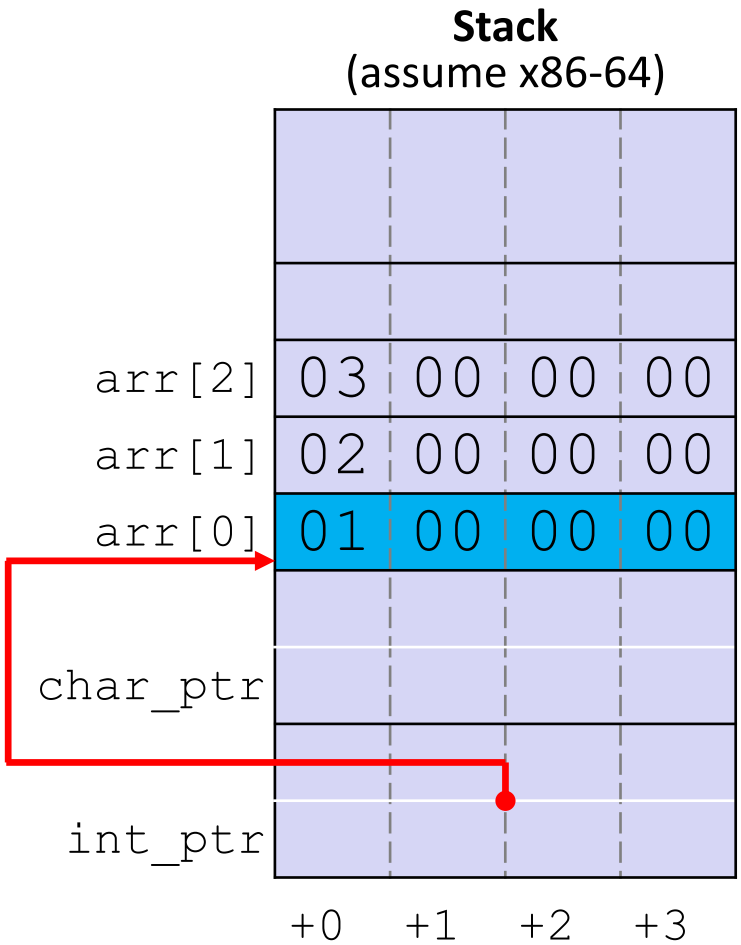


Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
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 0;
}
```

pointerarithmetic.c

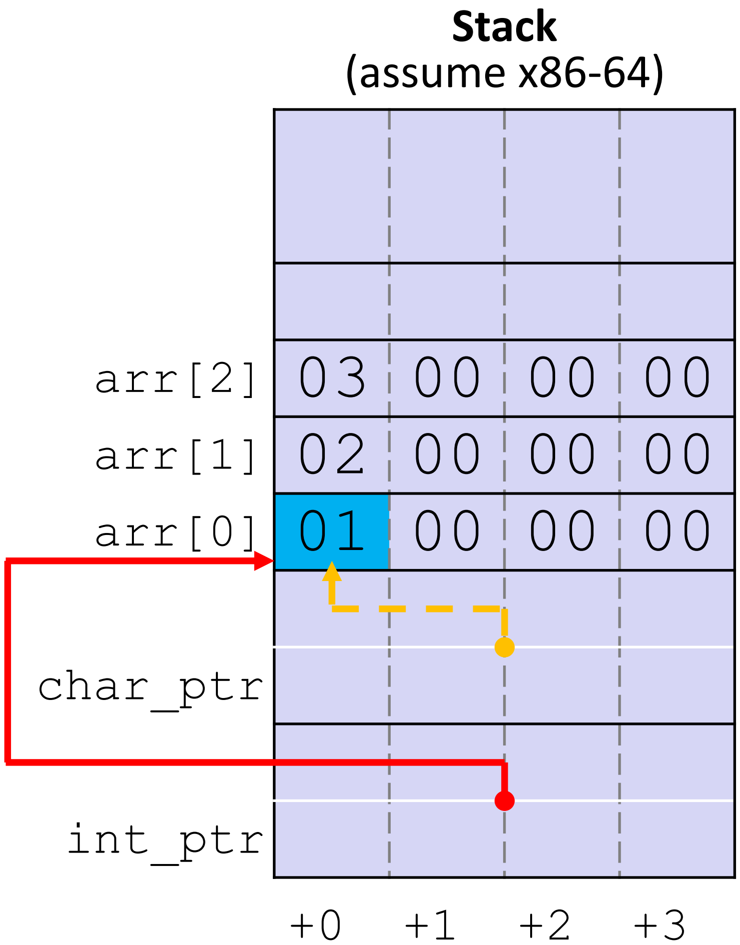


Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
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 0;
}
```

pointerarithmetic.c



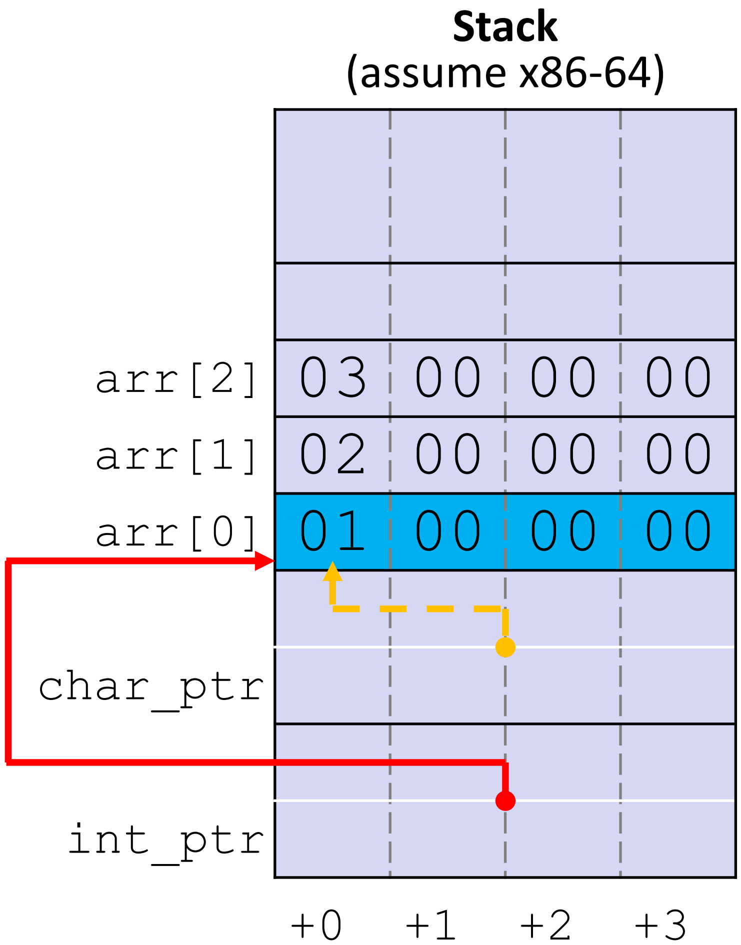
Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
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 0;
}
```

pointerarithmetic.c

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



Pointer Arithmetic Example

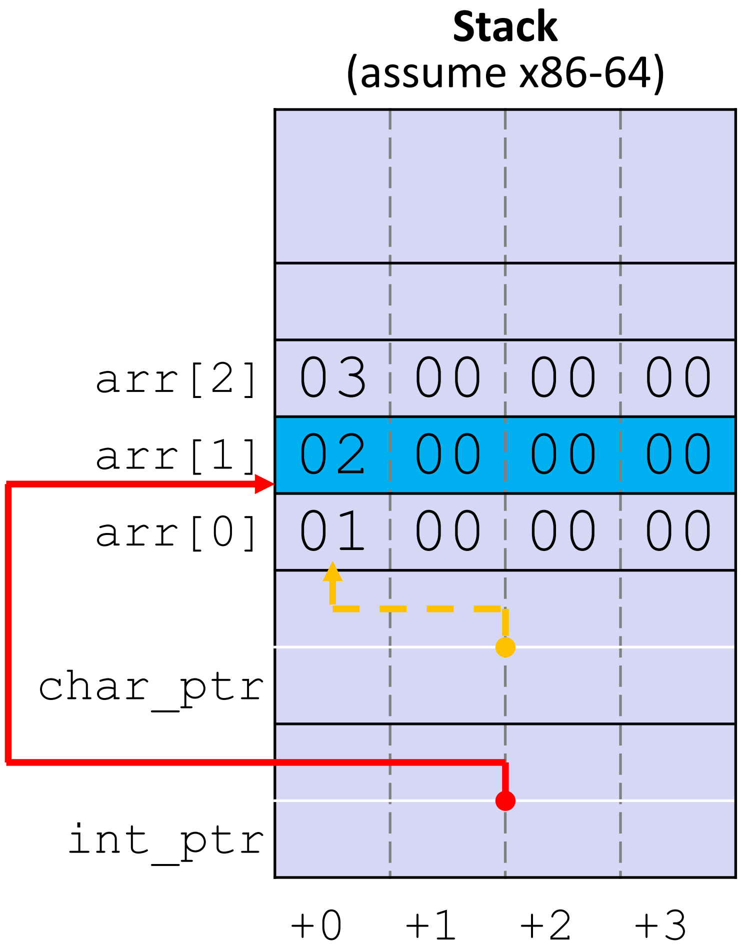
Note: Arrow points to *next* instruction.

```
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 0;
}
```

pointerarithmetic.c

int_ptr: 0x0x7ffffffde014

***int_ptr:** 2

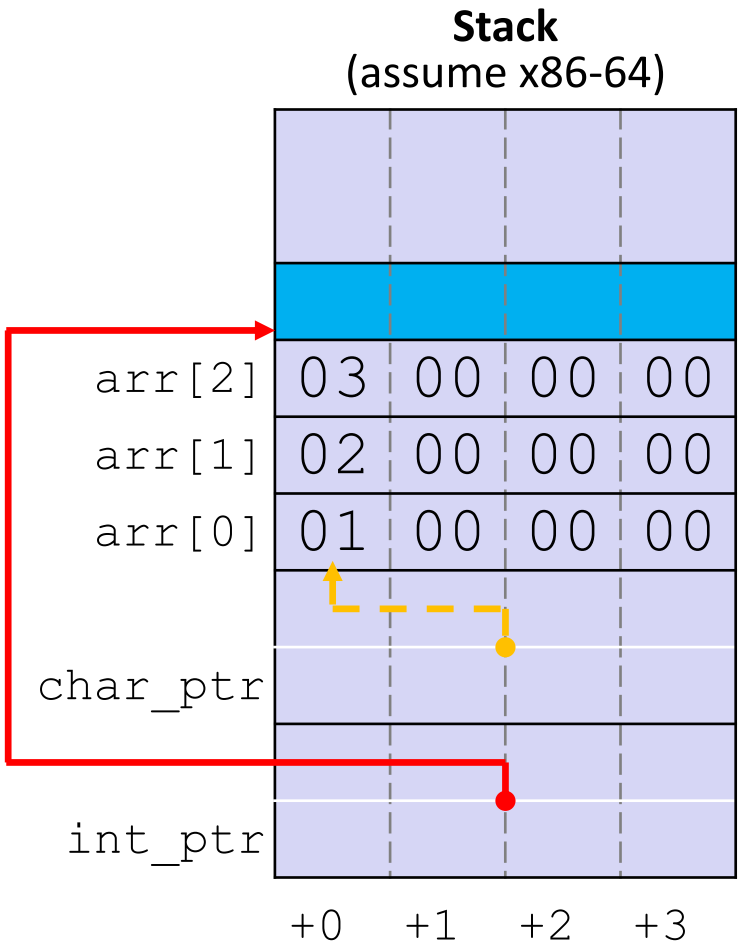


Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```c
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 0;
}
```

pointerarithmetic.c



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

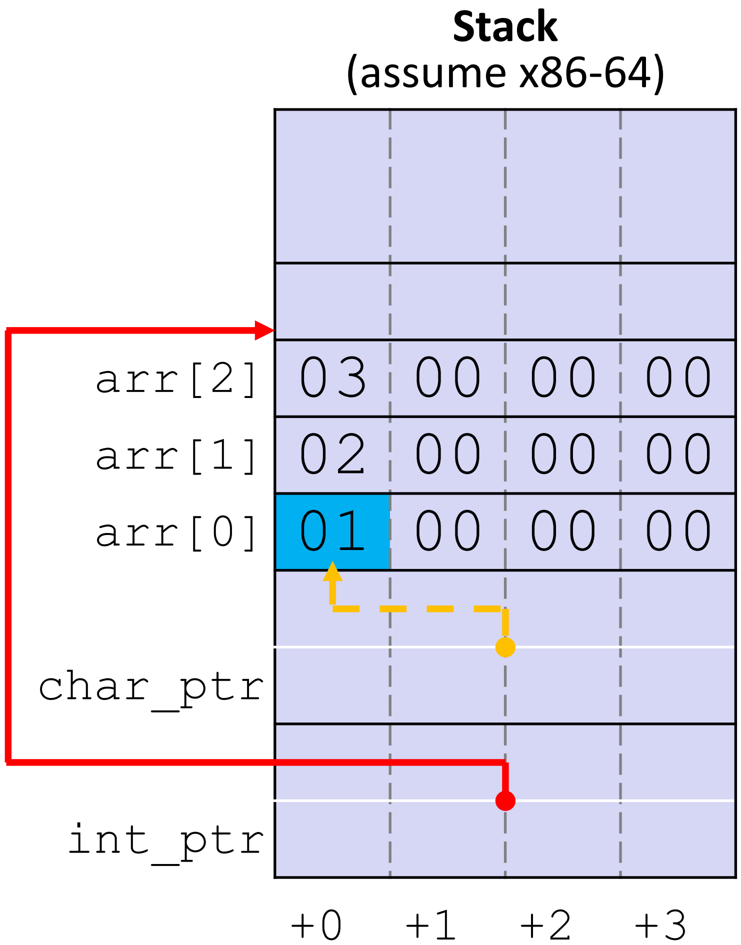
Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
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 0;
}
```

pointerarithmetic.c

char_ptr: 0x0x7fffffde010
***char_ptr:** 1



Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
int main(int argc, char **argv) {
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  char_ptr += 1;
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  return 0;
}
```
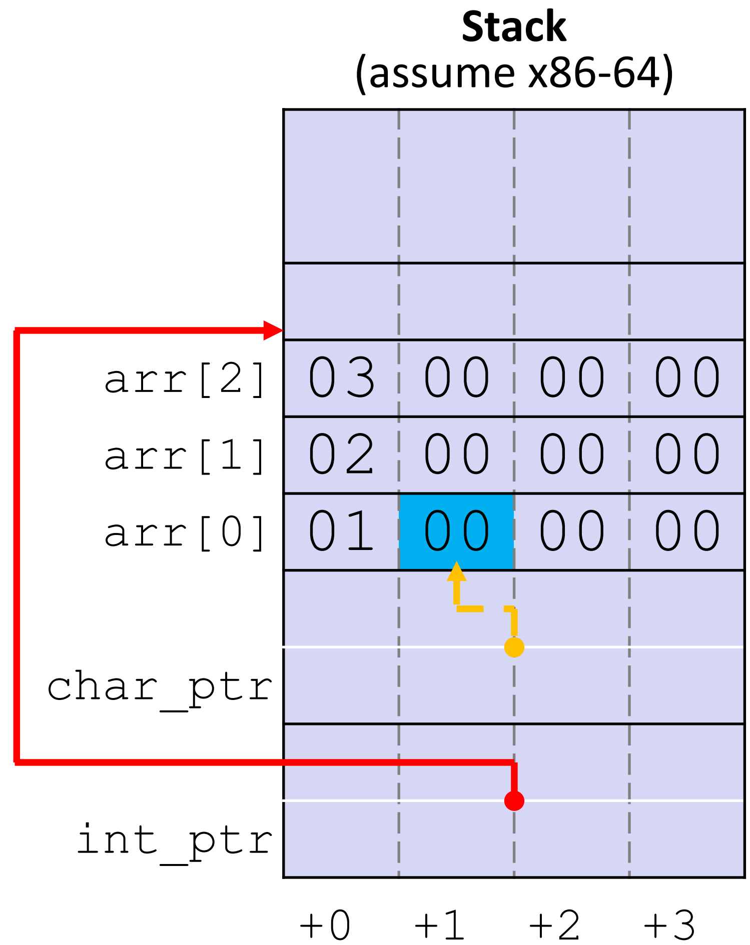

pointerarithmetic.c



char_ptr: 0x0x7ffffffde011

***char_ptr:** 0

Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

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

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

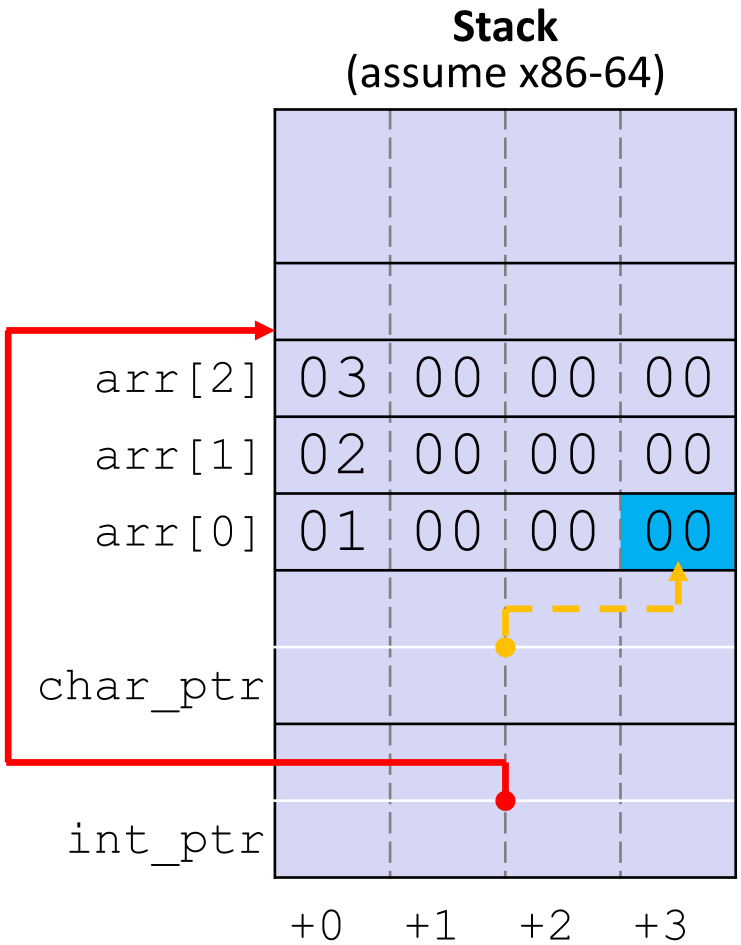
  char_ptr += 1;
  char_ptr += 2;

  return 0;
}
```

pointerarithmetic.c

char_ptr: 0x0x7ffffffde013

***char_ptr:** 0



Lecture Outline

- Pointers & Pointer Arithmetic
- **Pointers as Parameters**
- Pointers and Arrays
- Function Pointers

C is Call-By-Value

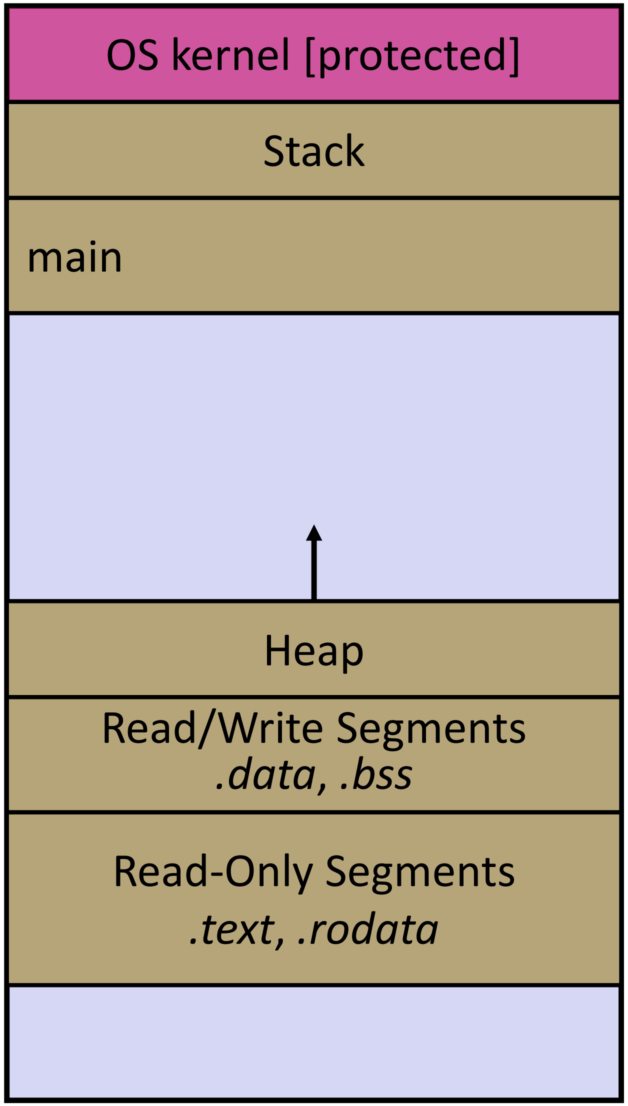
- C (and Java) pass arguments by *value*
  - Callee receives a **local copy** of the argument
    - Register or Stack
  - If the callee modifies a parameter, the caller's copy *isn't* modified

```
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.

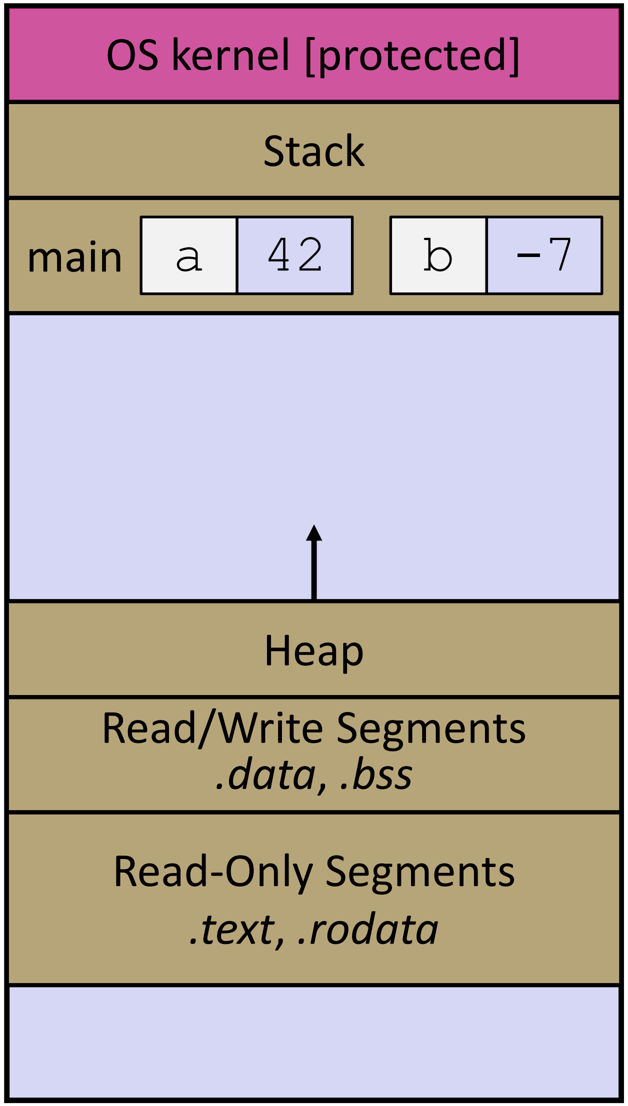


brokenswap.c

```
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



brokenswap.c

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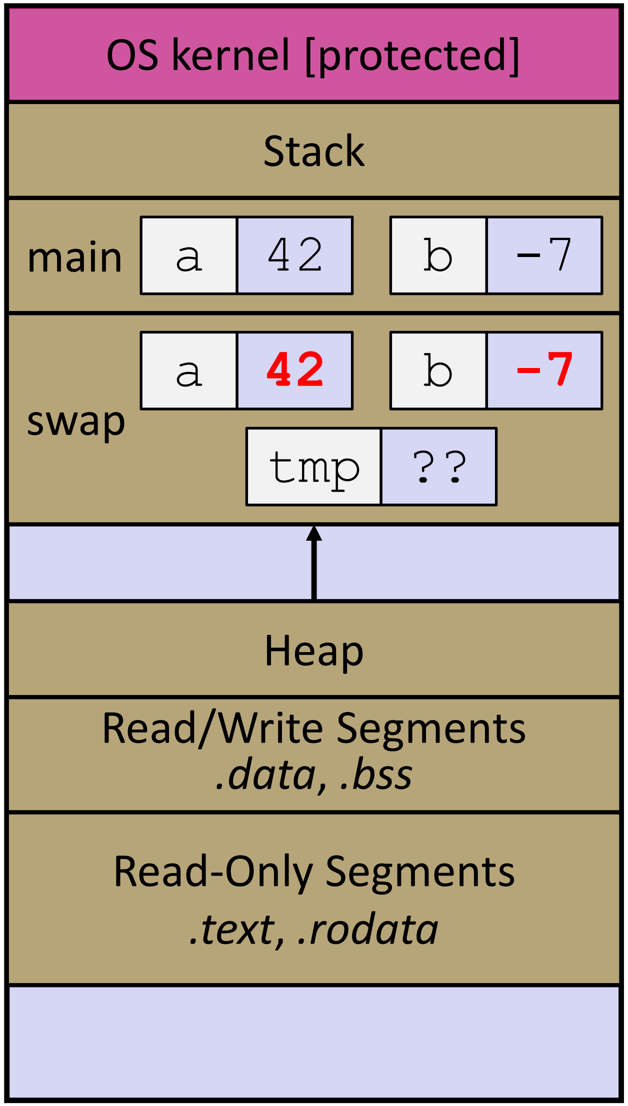
Broken Swap



brokenswap.c

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  a = b;
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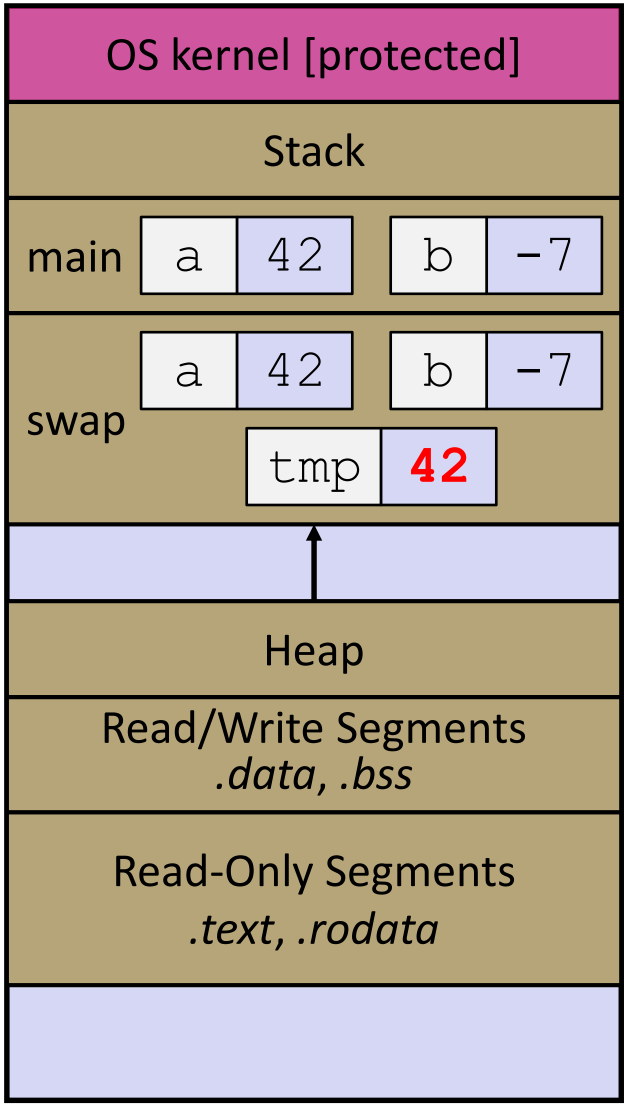
Broken Swap



brokenswap.c

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  ...
```

Broken Swap

brokenswap.c

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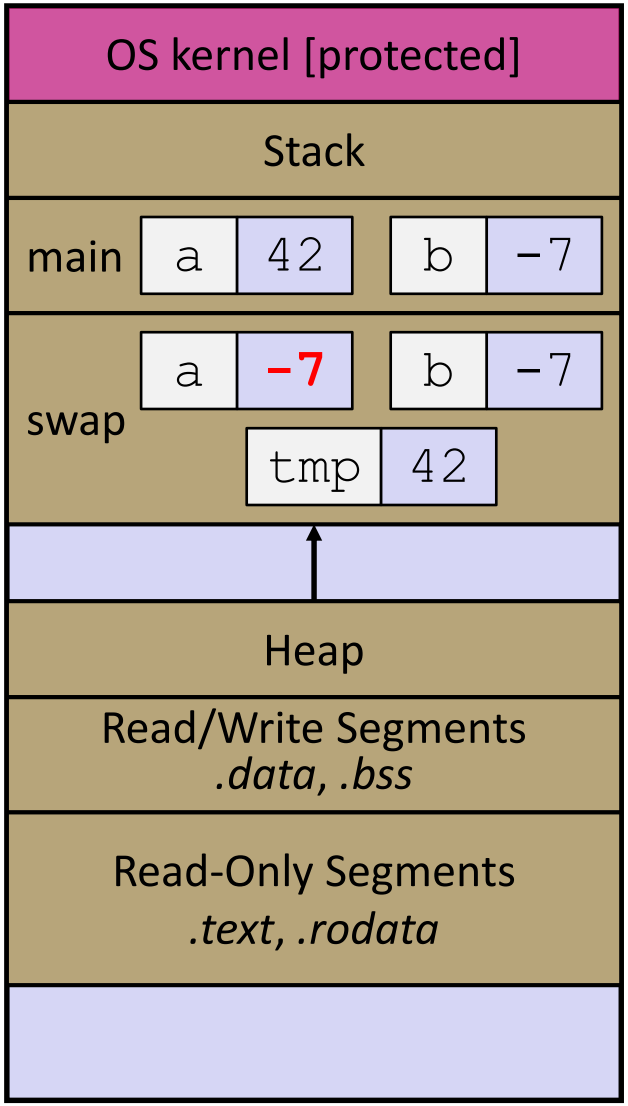
  swap(a, b);
  ...
```



Broken Swap

brokenswap.c

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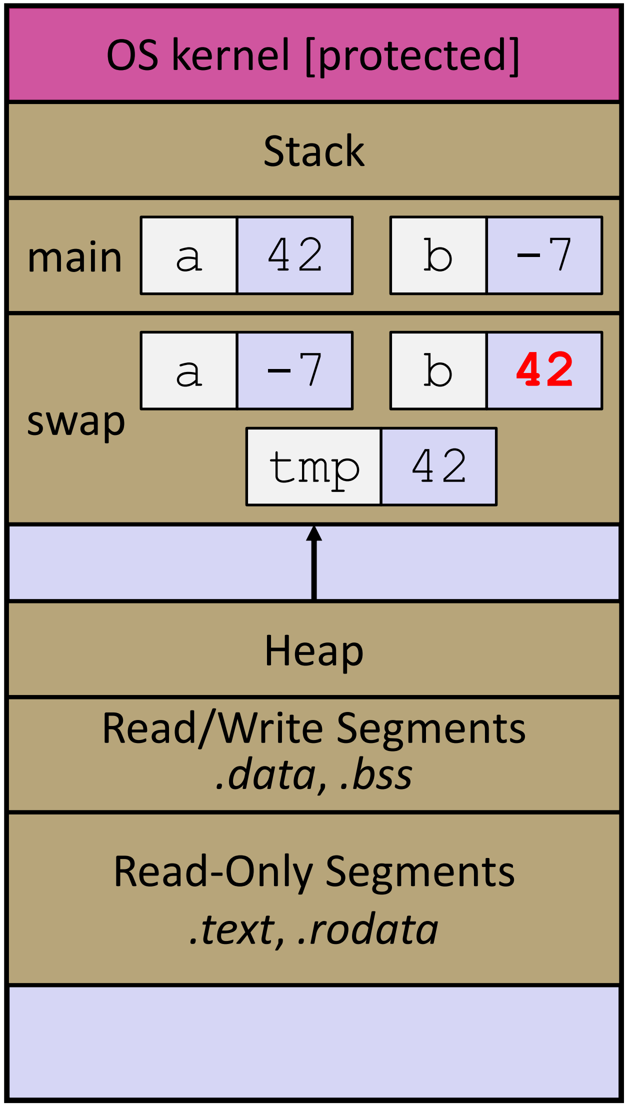

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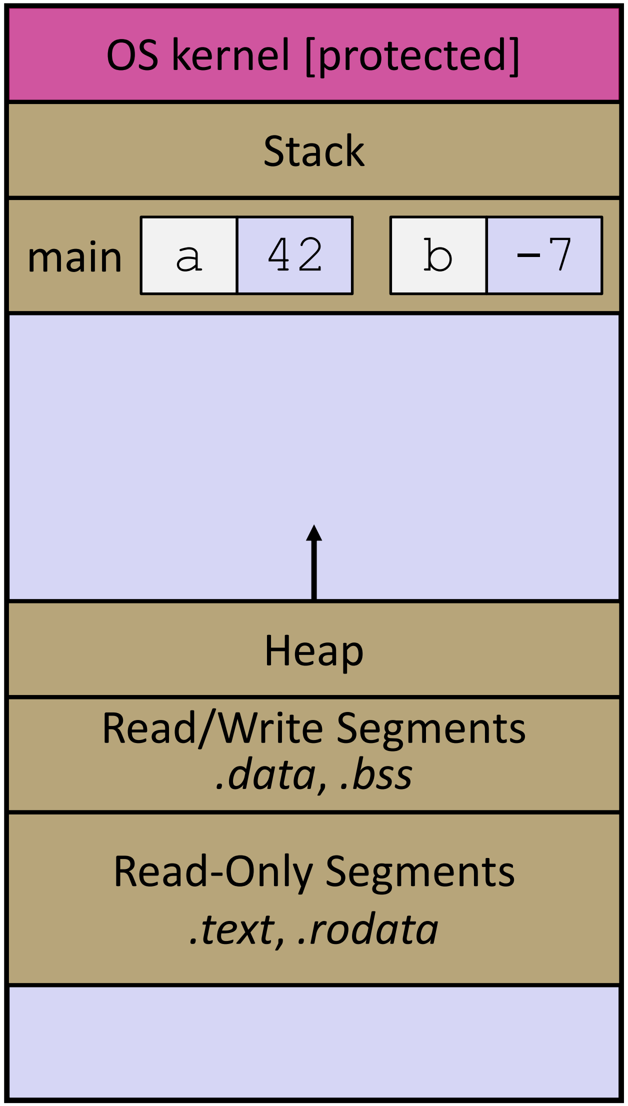

brokenswap.c

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  a = b;
  b = tmp;
}

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

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

```c
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);
  ...
```

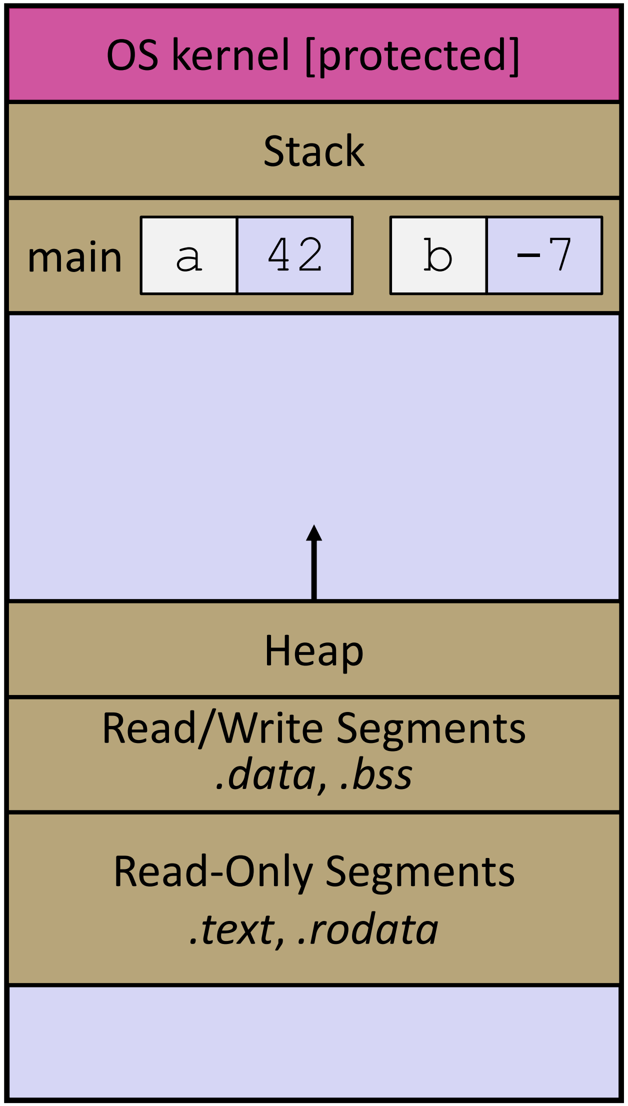
Fixed Swap

Note: Arrow points to *next* instruction.

swap.c

```
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

swap.c

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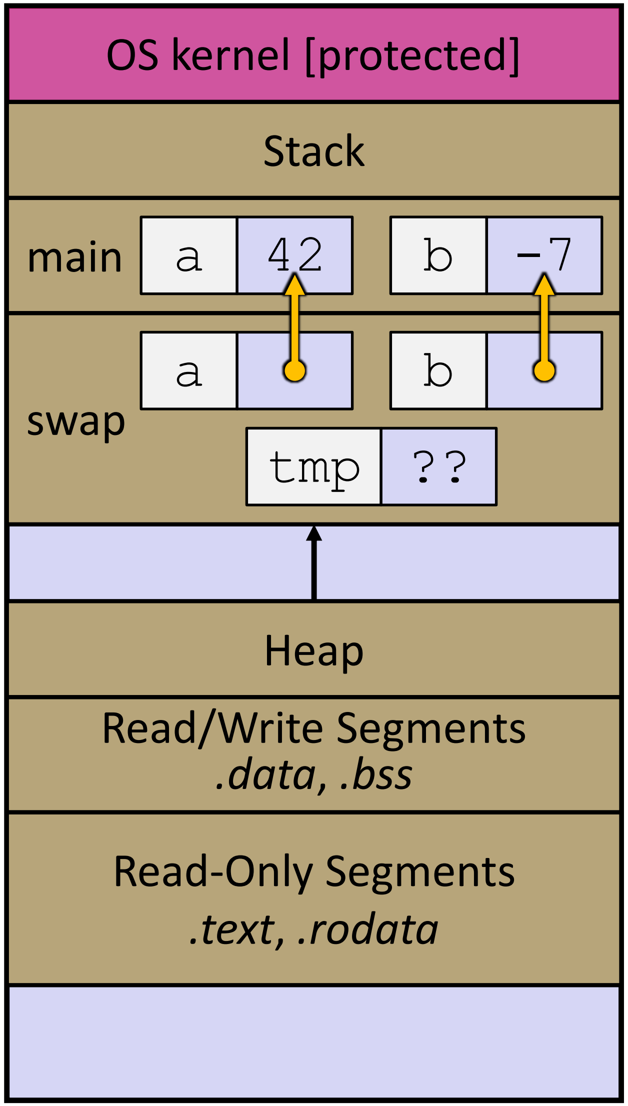
}

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

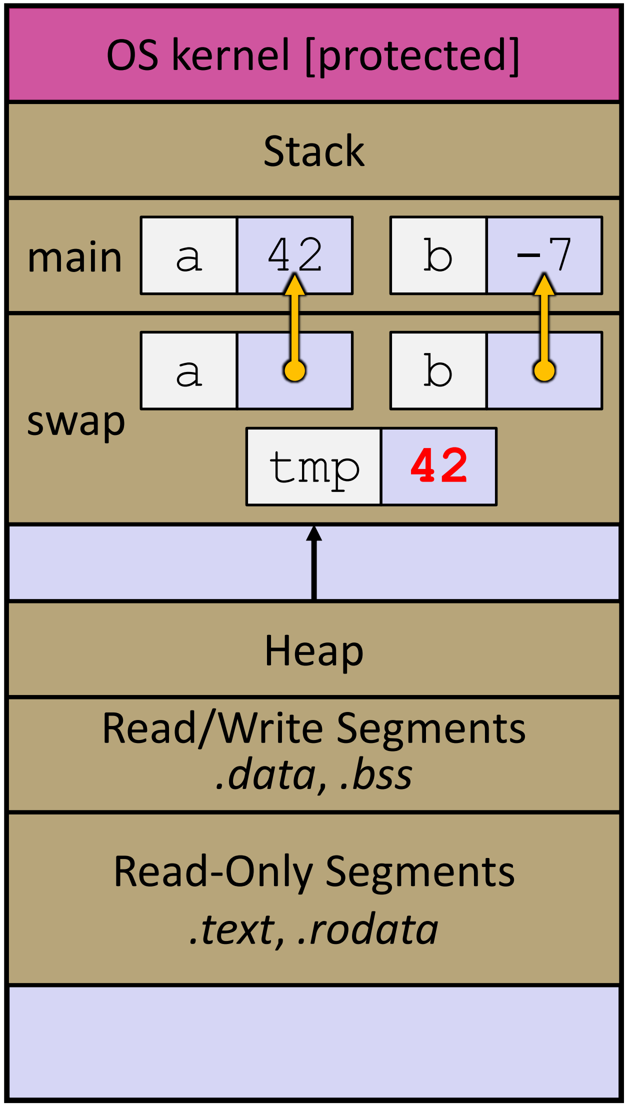


Fixed Swap

swap.c

```
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);
  ...
```



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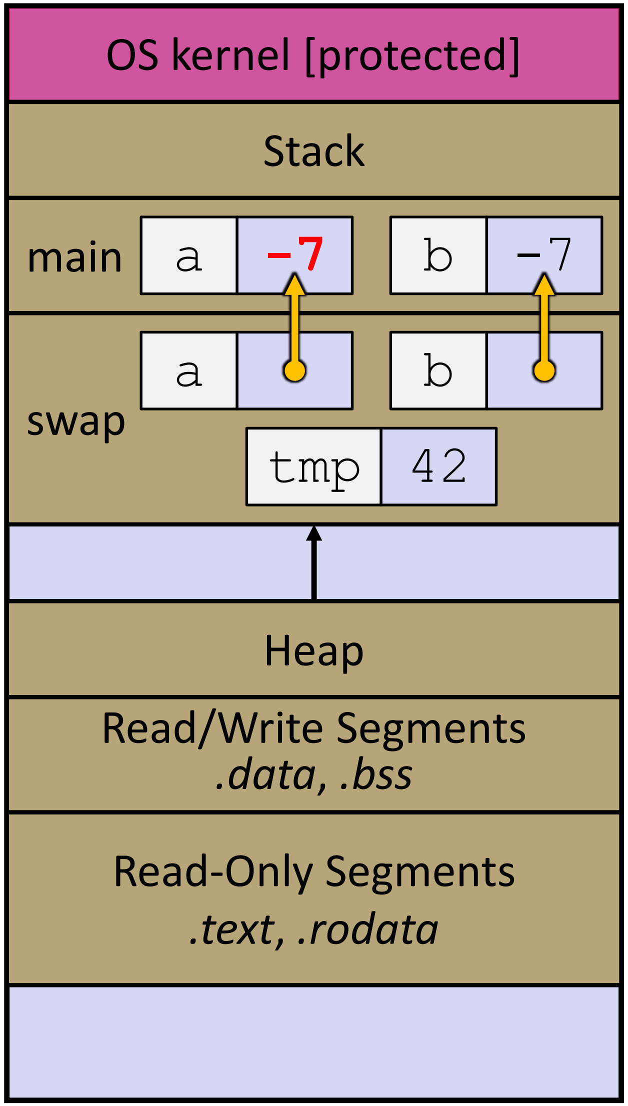

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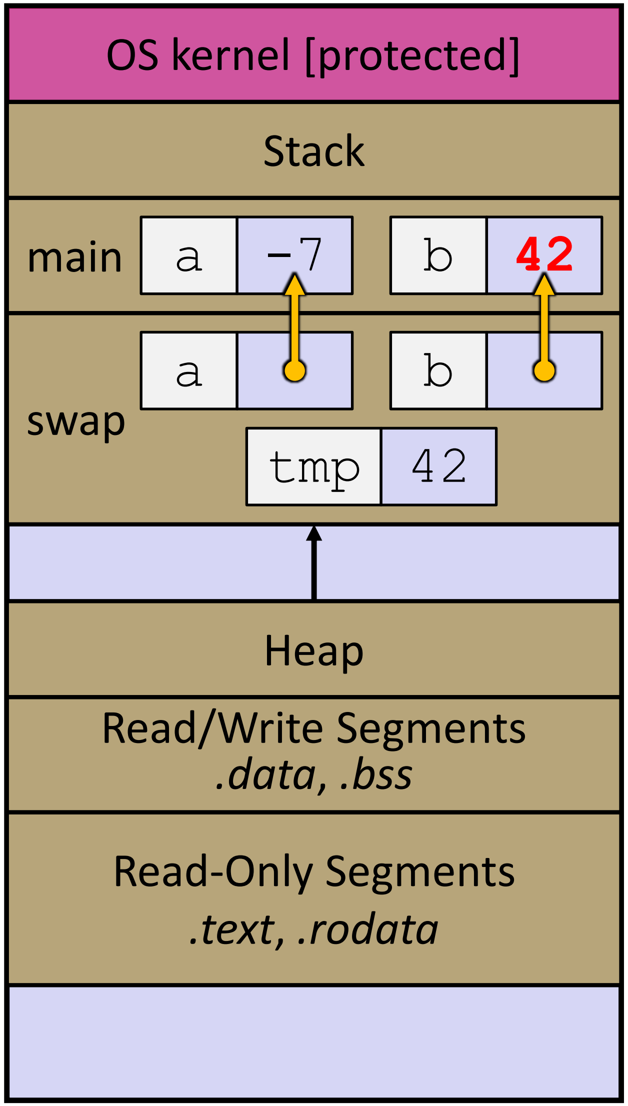

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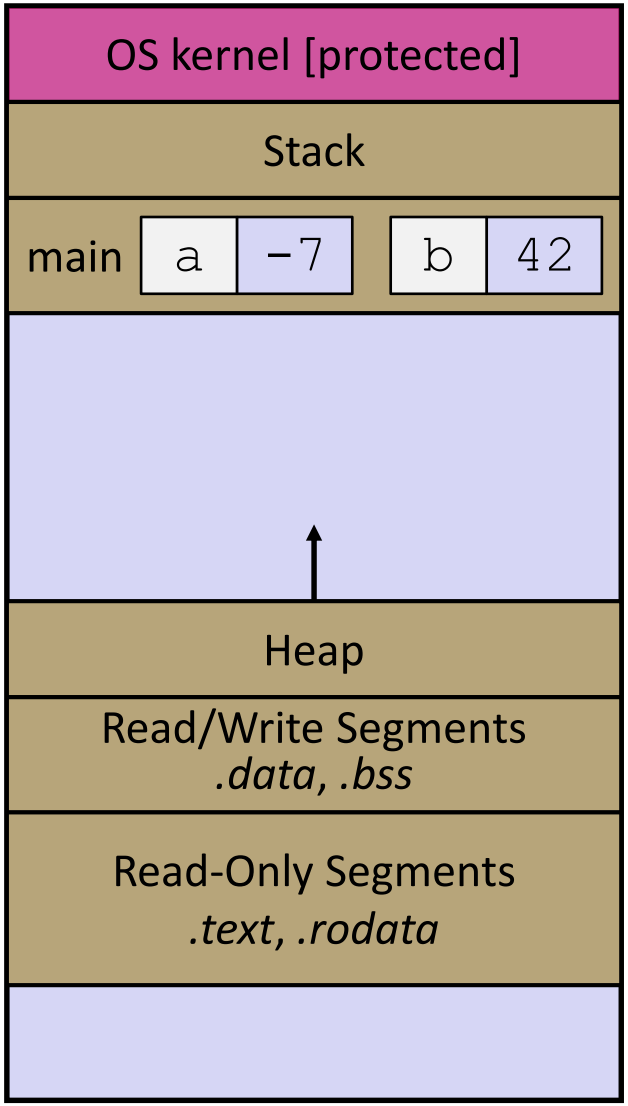

Lecture Outline

- Pointers & Pointer Arithmetic
- Pointers as Parameters
- **Pointers and Arrays**
- Function Pointers

Pointers and Arrays

a[3] = *(a+3)

- A pointer can point to an array element
  - You can use array indexing notation on pointers
    - `a[i]` is `*(a+i)` with pointer arithmetic – reference the data `i` elements forward from `a`
  - 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 b/c it doesn't have any storage associated with it

```
int a[] = {10, 20, 30, 40, 50};
int32_t *p1 = &a[3];   // refers to a's 4th element
int32_t *p2 = &a[0];   // refers to a's 1st element
int32_t *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
```

Pointers and Arrays

```
int a[] = {10, 20, 30, 40, 50};
int32_t *p1 = &a[3];  // refers to a's 4th element
int32_t *p2 = &a[0];  // refers to a's 1st element
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*p1 = 100;
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p1[1] = 300;
p2[1] = 400;
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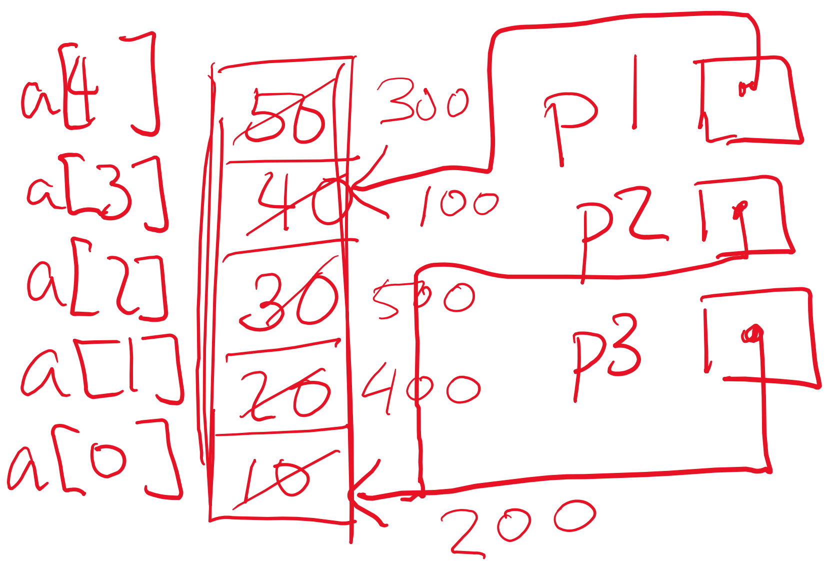
```



Note: there is no variable "a" (no memory associated with the label "a"), just its elements

Array Parameters

a[5] === *(a+5) === *(5+a) === 5[a]!

- 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

array subscripting is the same as pointer arithmetic under the covers!

This code:

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

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

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

Equivalent to:

```
void f(int *a);

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

void f(int *a) {
```

Lecture Outline

- Pointers & Pointer Arithmetic
- Pointers as Parameters
- Pointers and Arrays
- **Function Pointers**

Function Pointers

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

- Generic format:

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

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

can also use:
name(arg1, ...)

- 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

```
#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

Variable name

Variable type

map.c

Lecture Outline

- Pointers & Pointer Arithmetic
- Pointers as Parameters
- Pointers and Arrays
- Function Pointers

"Pointers are merely variables that contain memory addresses"

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