Poll Everywhere

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About how long did Exercises 0 and 1 take you? (two polls)

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn't submit / I prefer not to say

Systems Programming
Pointers

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Relevant Course Information (1/3)

- Exercise grading (see Ed post #53)
  - Autograder scores visible immediately after deadline; sample solutions released same day as deadline
  - Grades (out of 8):
    - Correctness: Output (3)
    - Tools: Compilation (1), Valgrind (1)
    - Style: Linter (1), Other Style [manual] (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)

- Pre-quarter survey (Canvas quiz) due tonight
- Exercise 2 out today and due Monday (1/12) morning
  - First exercise submitted via Gitlab tagging (`ex2-submit`)
  - Make a private Ed post if you don't have your exercise repo yet
- Homework 1 out tonight, due in 2 weeks (Thu 1/22)
  - Linked list and hash table implementations in C
  - Get starter code by cloning your new *homework* repo

Relevant Course Information (3/3)

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

Lecture Outline (1/4)

- **Pointer Basics**
- Pointer Arithmetic
- Pointers as Parameters
- Function Pointers

Pointers

- Variables that store addresses
  - It points to somewhere in the process' virtual address space
  - `&foo` produces the virtual address of `foo`
- Generic definition: `type* name;` or `type *name;`
  - Recommended: do not define multiple pointers on same line:

```
int *p1, p2;
```

not the same as

```
int *p1, *p2;
```

  - Instead, use:

```
int *p1;
int *p2;
```

- *Dereference* a pointer using the unary `*` operator
  - Access the memory referred to by a pointer

Box-and-Arrow Diagrams (1/4)

boxarrow.c

%rdi %rsi

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

need address, must be in stack

address | **name** | value

Box-and-Arrow Diagrams (2/4)

boxarrow.c

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

Box-and-Arrow Diagrams (3/4)

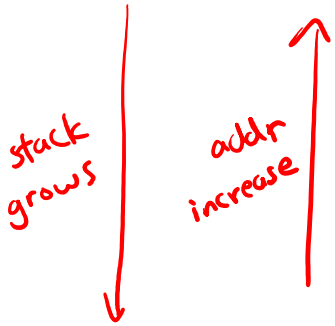
boxarrow.c

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

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 (4/4)

boxarrow.c

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

address	name	value
0x7fff…4c	x	1
0x7fff…48	arr[2]	4
0x7fff…44	arr[1]	3
0x7fff…40	arr[0]	2
0x7fff…38	p	0x7fff…44

p: get addr

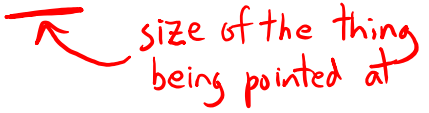
*p: get data at addr (follow arrow)

Lecture Outline (2/4)

- Pointer Basics
- **Pointer Arithmetic**
- Pointers as Parameters
- Function Pointers

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!
    - 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

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

ptr[i] ↔ *(ptr+i) ↔ *(i+ptr) ↔ i[ptr]

DON'T USE but all ptrs "under the hood"

```
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
```

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

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;
}
```

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}

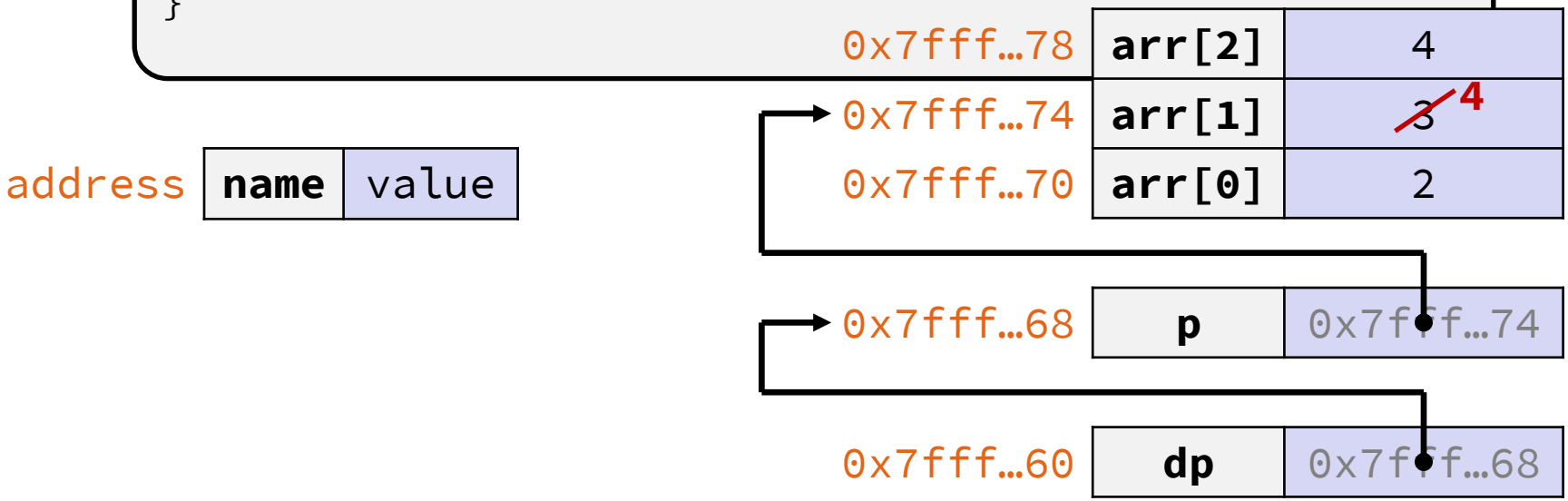
E. We're lost…

Practice Solution (1/4)

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

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;   // same as **dp += 1;
  p += 1;
  *(*dp) += 1;

  return EXIT_SUCCESS;
}
```

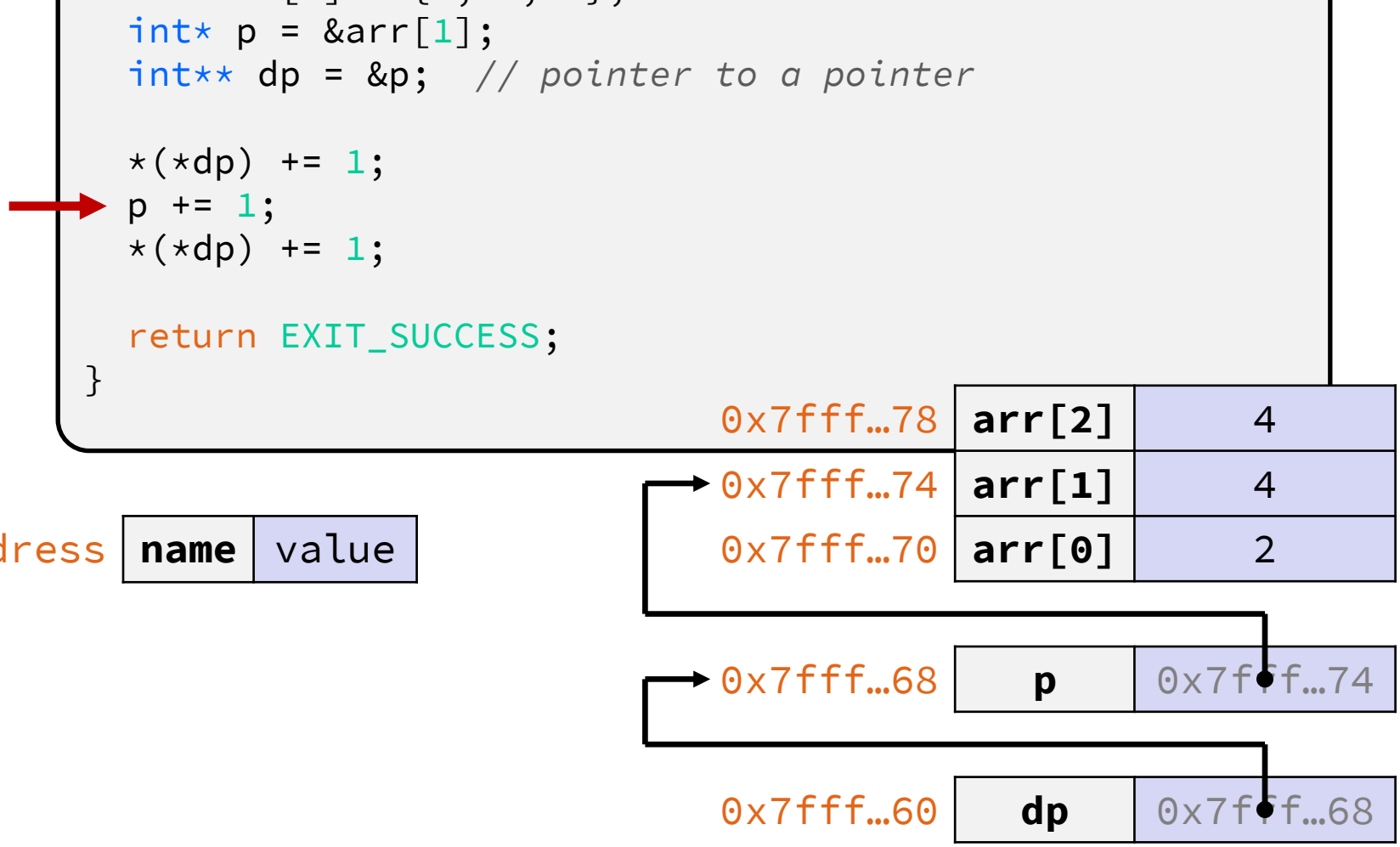


Practice Solution (2/4)

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

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;
}
```

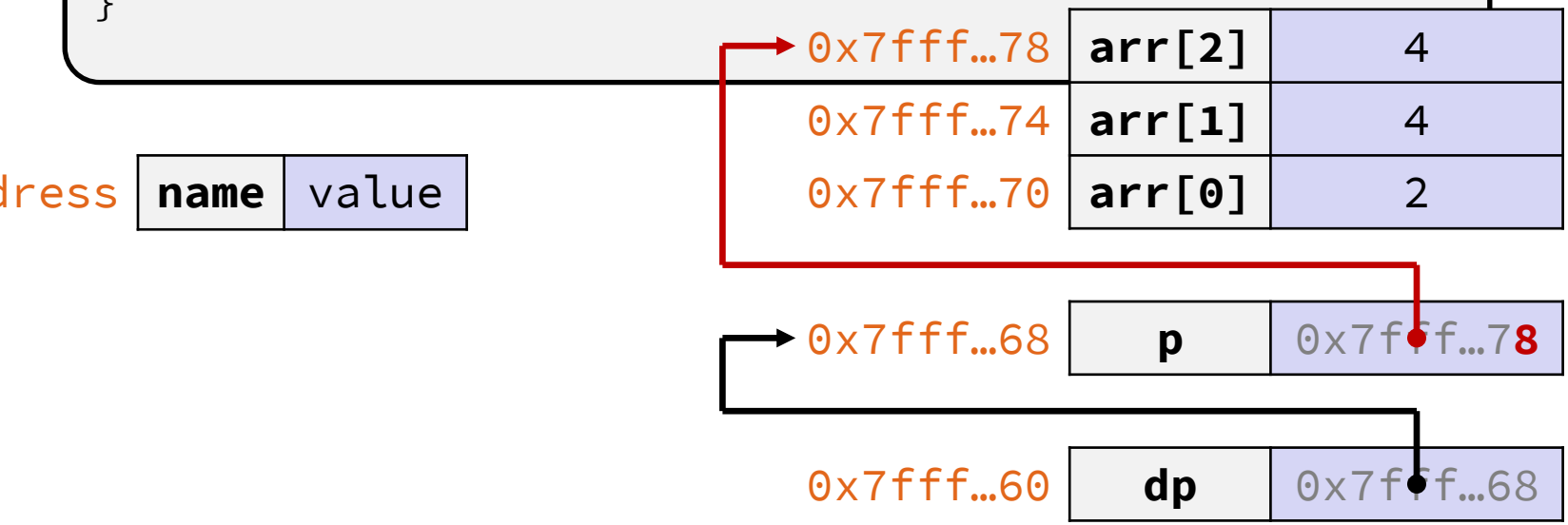


Practice Solution (3/4)

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

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;
}
```

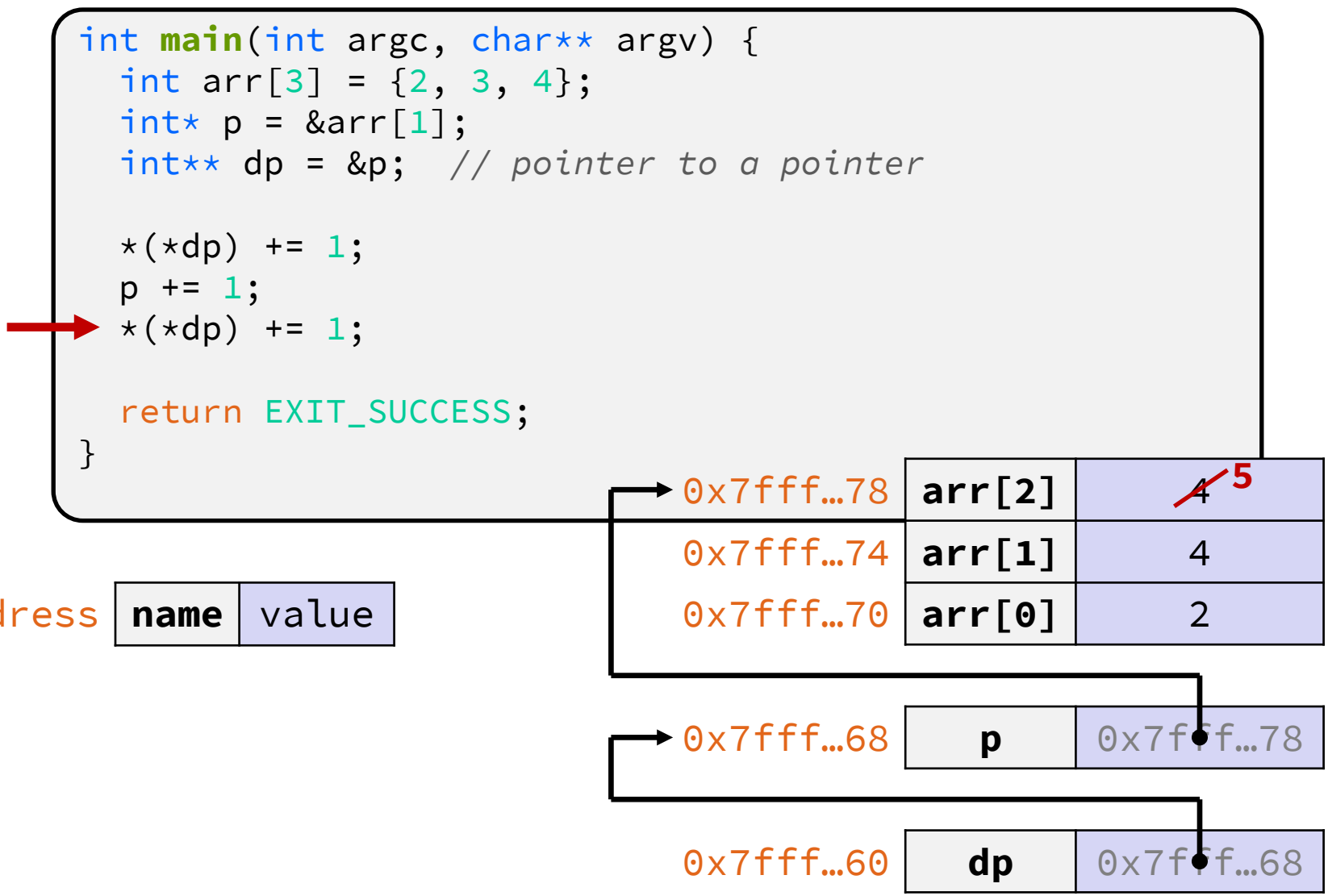


Practice Solution (4/4)

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

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;
}
```

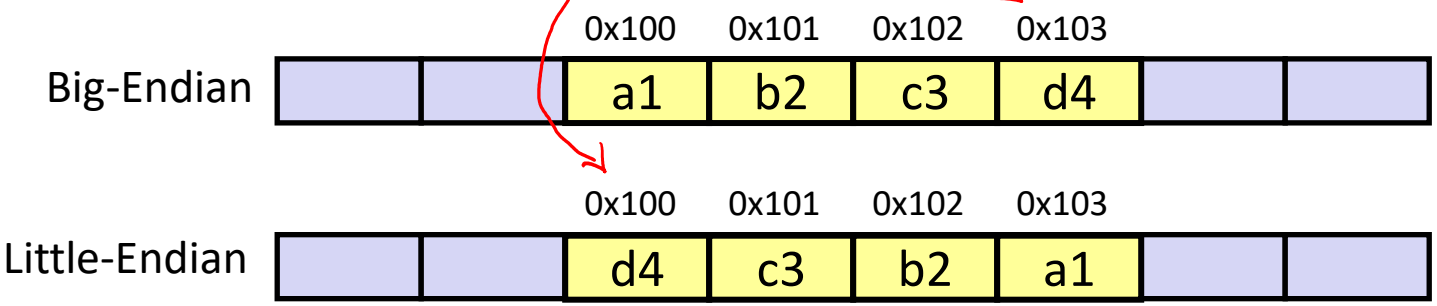


Endianness

- 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/biggest* address
  - Little-endian: Least significant byte has *lowest/littlest* address

(x86-64)

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

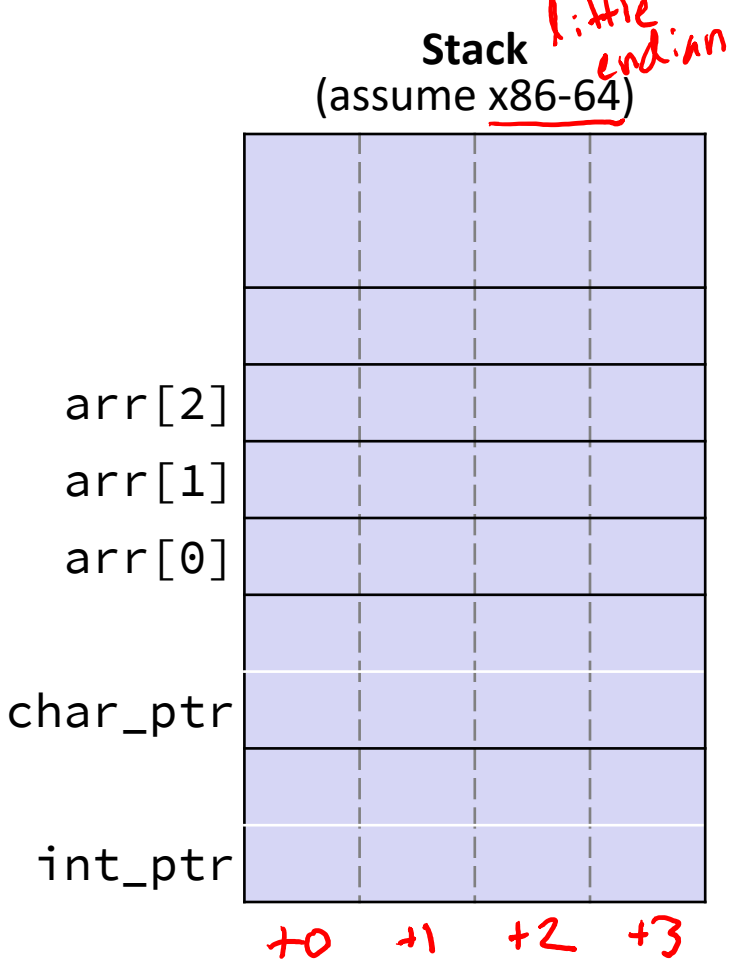


Pointer Arithmetic Example (1/10)

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 EXIT_SUCCESS;
}
```

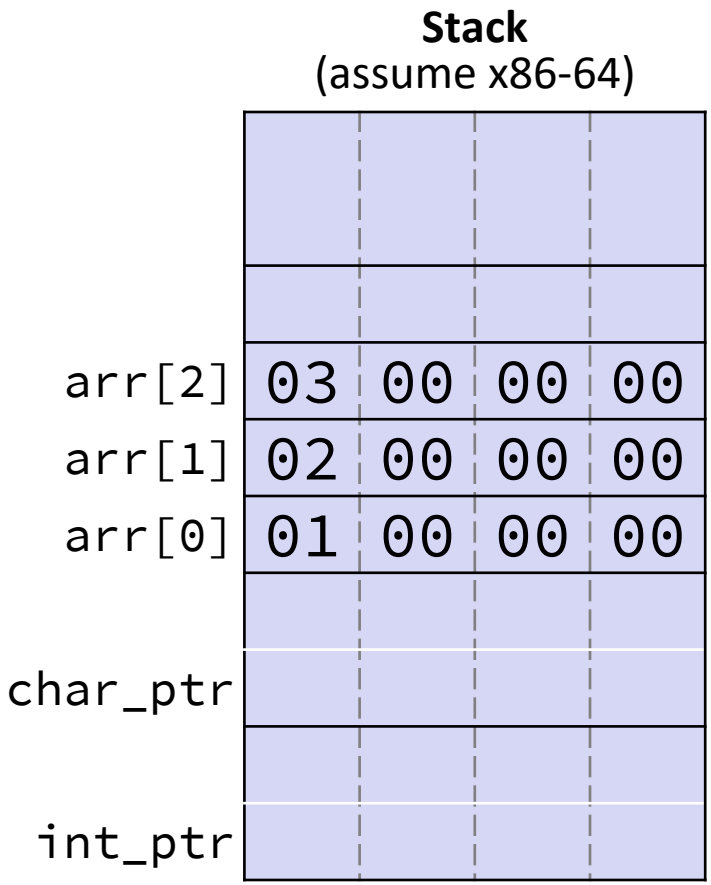
pointerarithmetic.c



Pointer Arithmetic Example (2/10)

```
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;
}
```

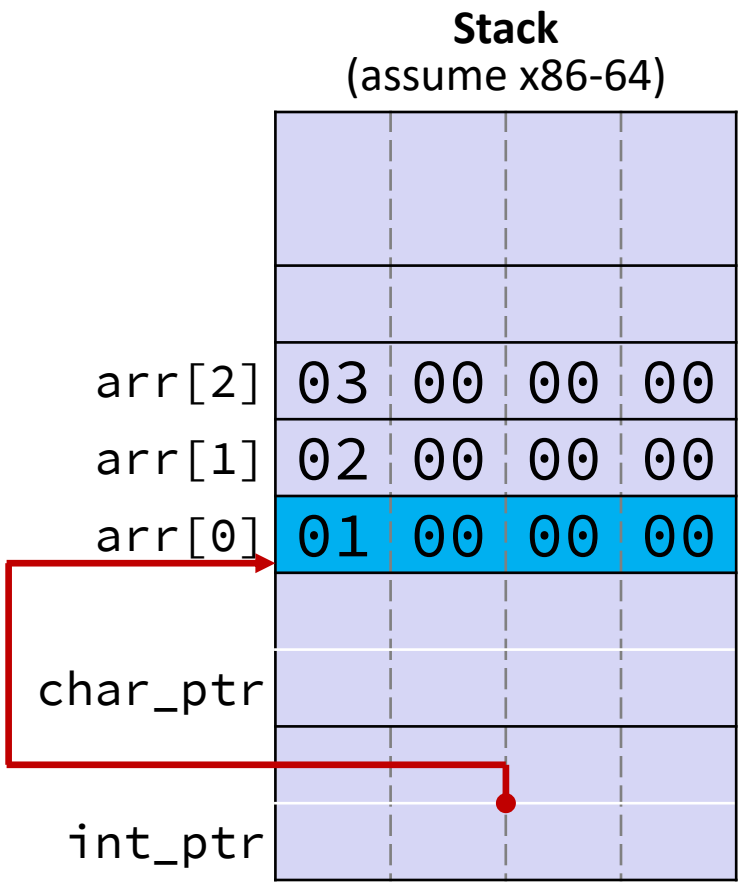
pointerarithmetic.c



Pointer Arithmetic Example (3/10)

```
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;
}
```

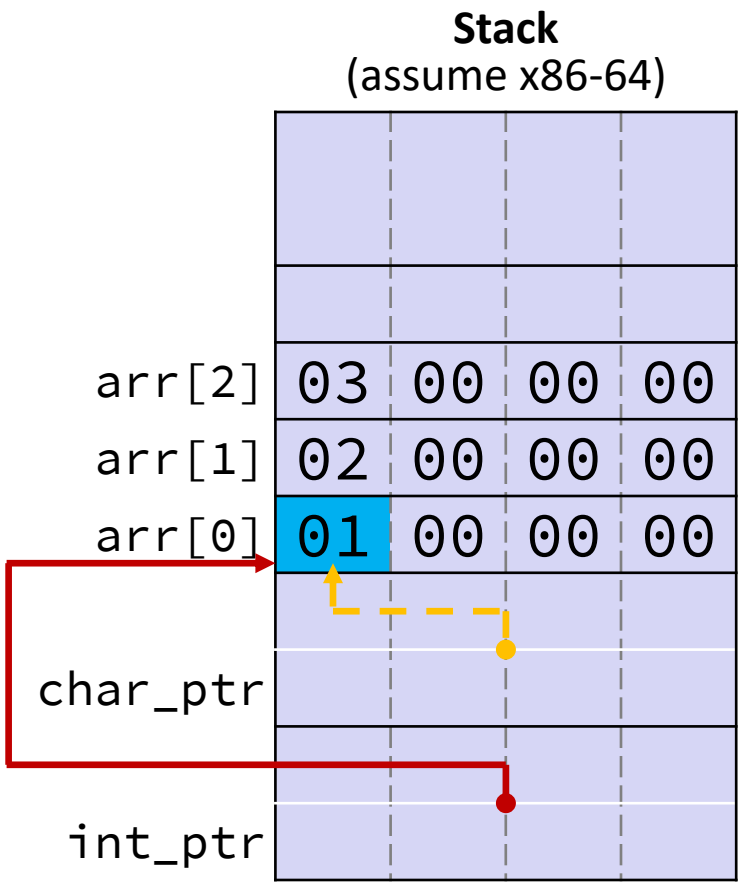
pointerarithmetic.c



Pointer Arithmetic Example (4/10)

```
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;
}
```

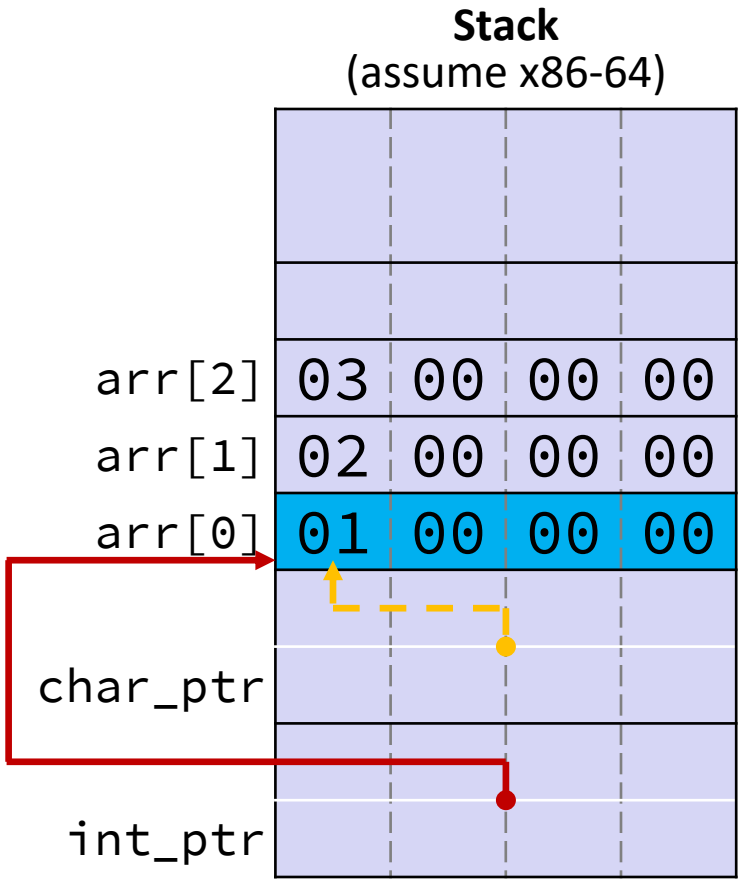
pointerarithmetic.c



Pointer Arithmetic Example (5/10)

```
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

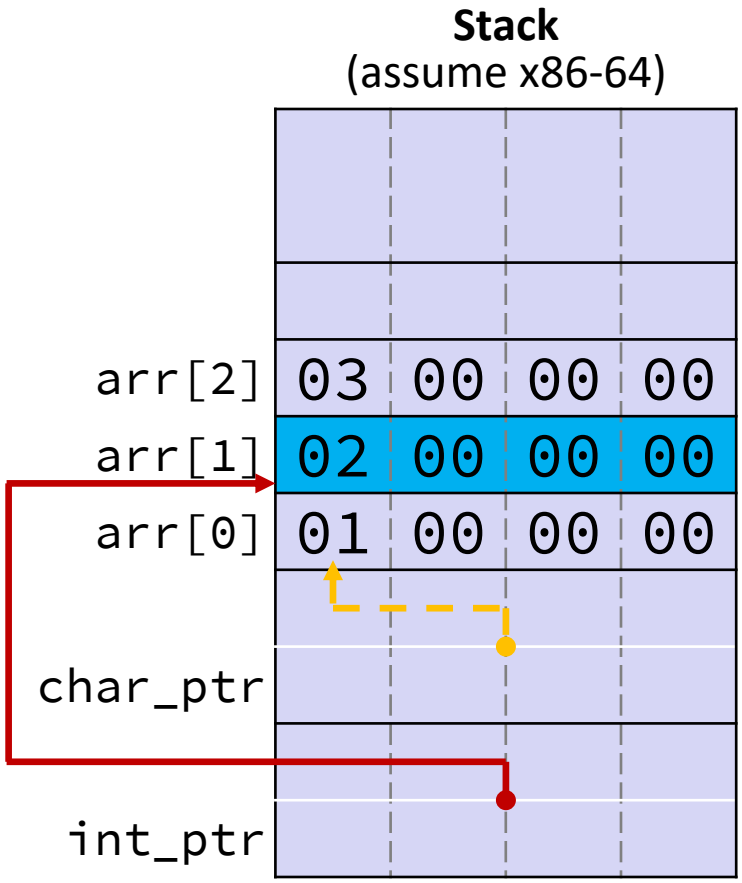



```
 int_ptr:   0x7fffffde010
*int_ptr:   1
```

Pointer Arithmetic Example (6/10)

```
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

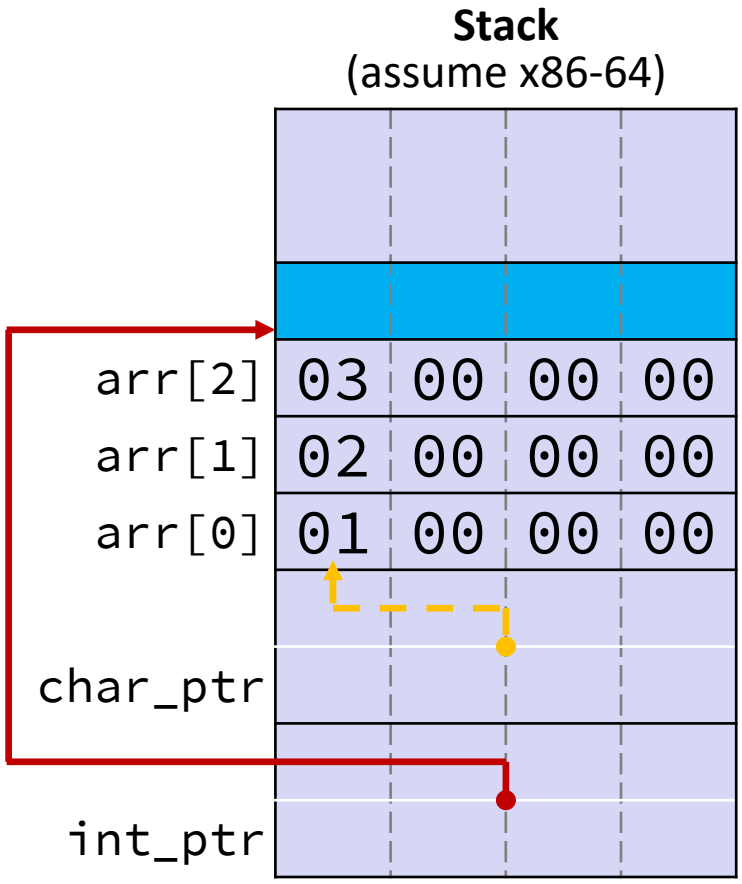



```
 int_ptr:   0x7fffffde014
*int_ptr:   2
```

Pointer Arithmetic Example (7/10)

```
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

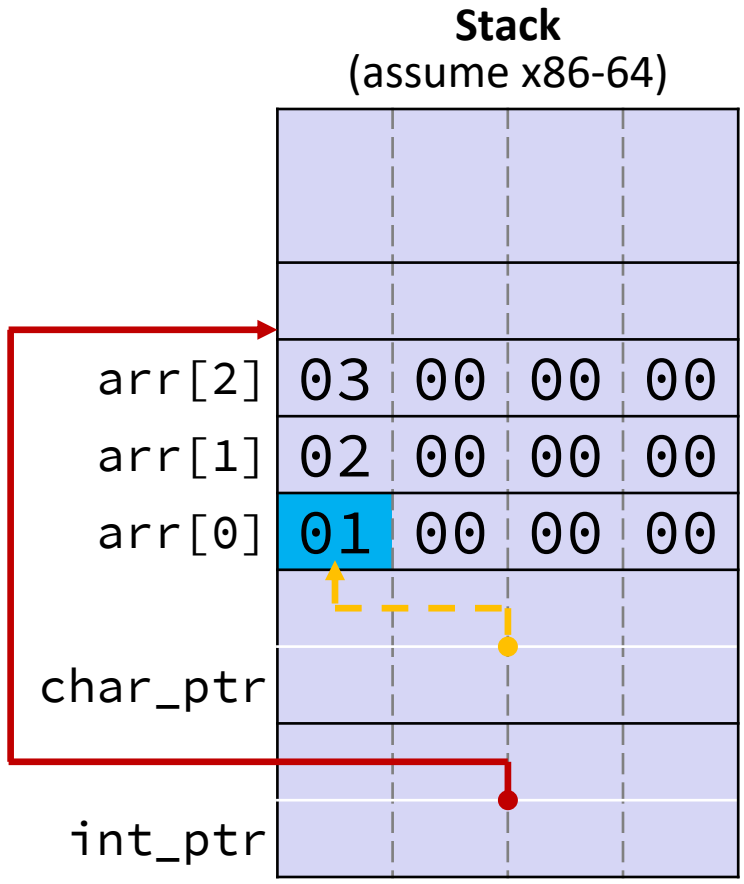


int_ptr: 0x7fffffde01c
***int_ptr:** ???

Pointer Arithmetic Example (8/10)

```
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

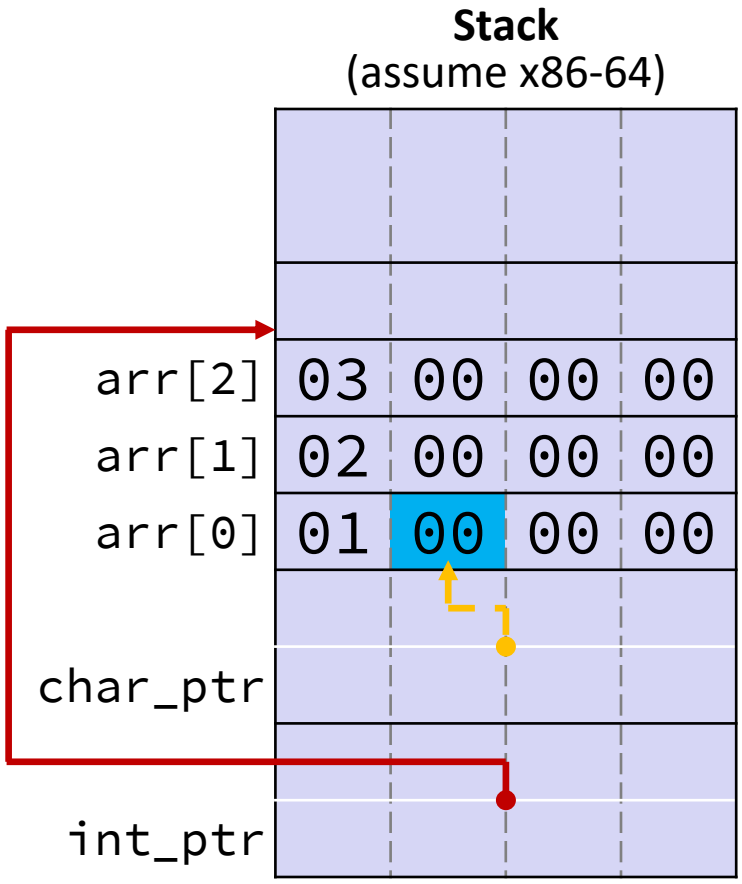


char_ptr: 0x7fffffde010
***char_ptr:** 1

Pointer Arithmetic Example (9/10)

```
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

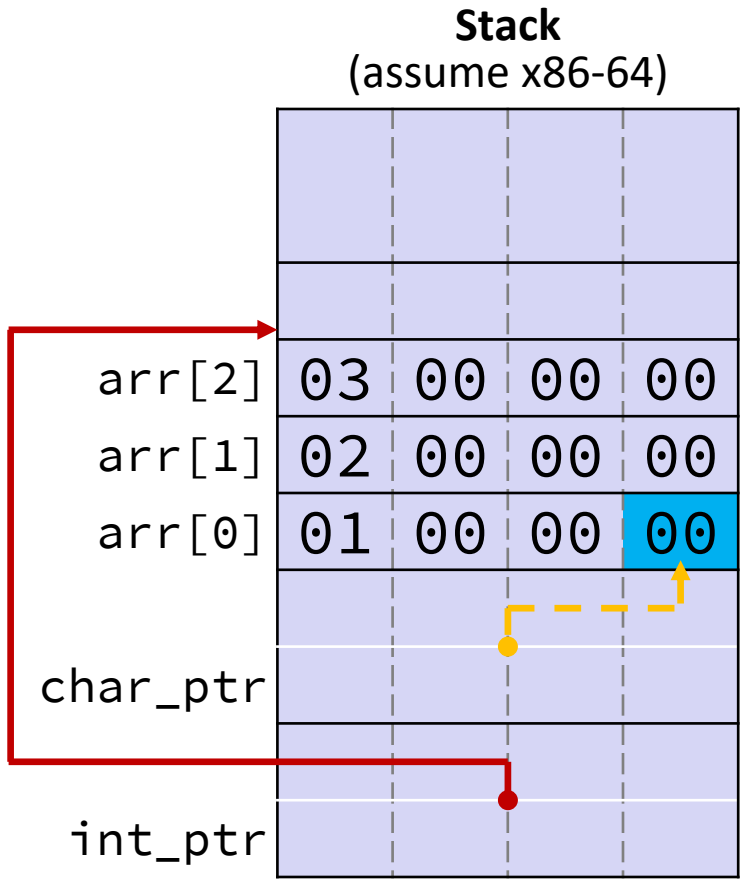


char_ptr: 0x7fffffde011
***char_ptr:** 0

Pointer Arithmetic Example (10/10)

```
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



char_ptr: 0x7fffffde013
***char_ptr:** 0

Lecture Outline (3/4)

- Pointer Basics
- Pointer Arithmetic
- **Pointers as Parameters**
- 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

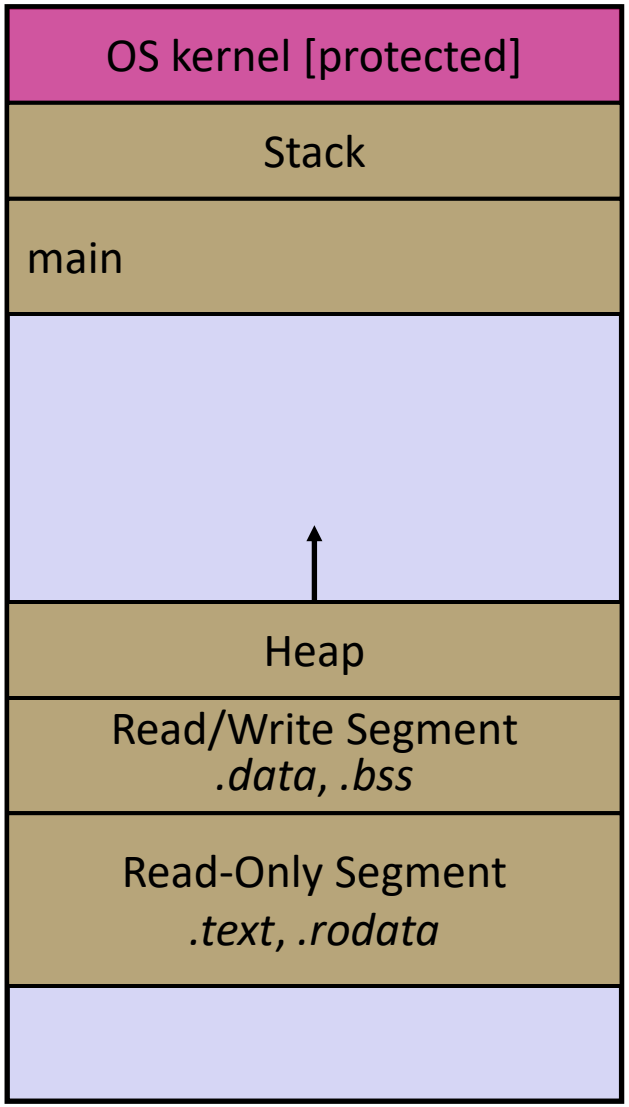
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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

Broken Swap (1/7)

Note: Arrow points to *next* instruction.

brokenswap.c

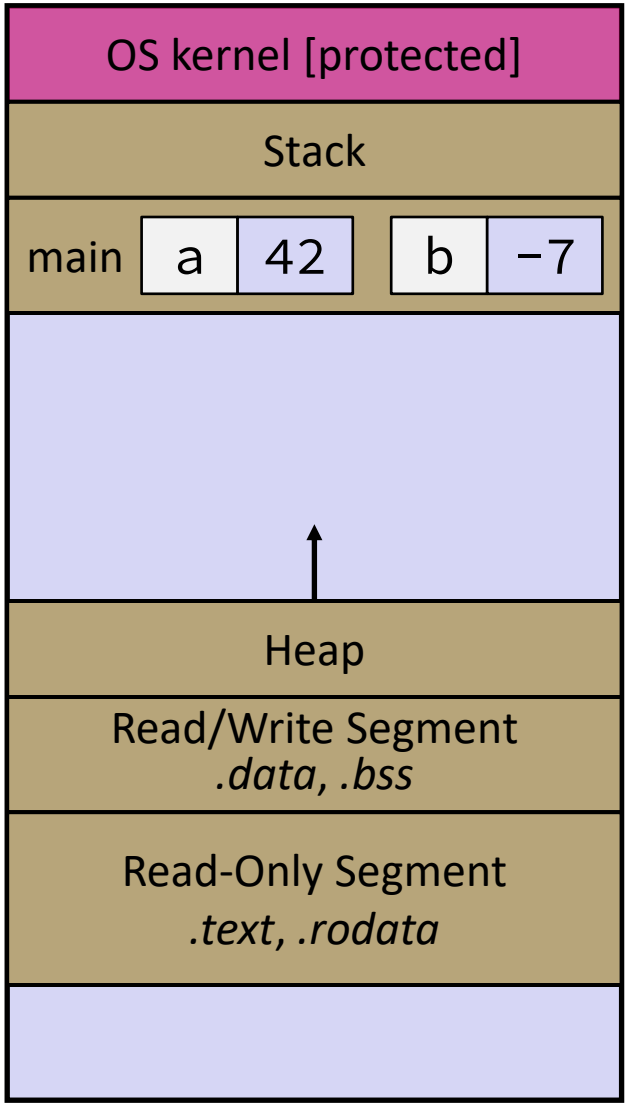
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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



Broken Swap (2/7)

brokenswap.c

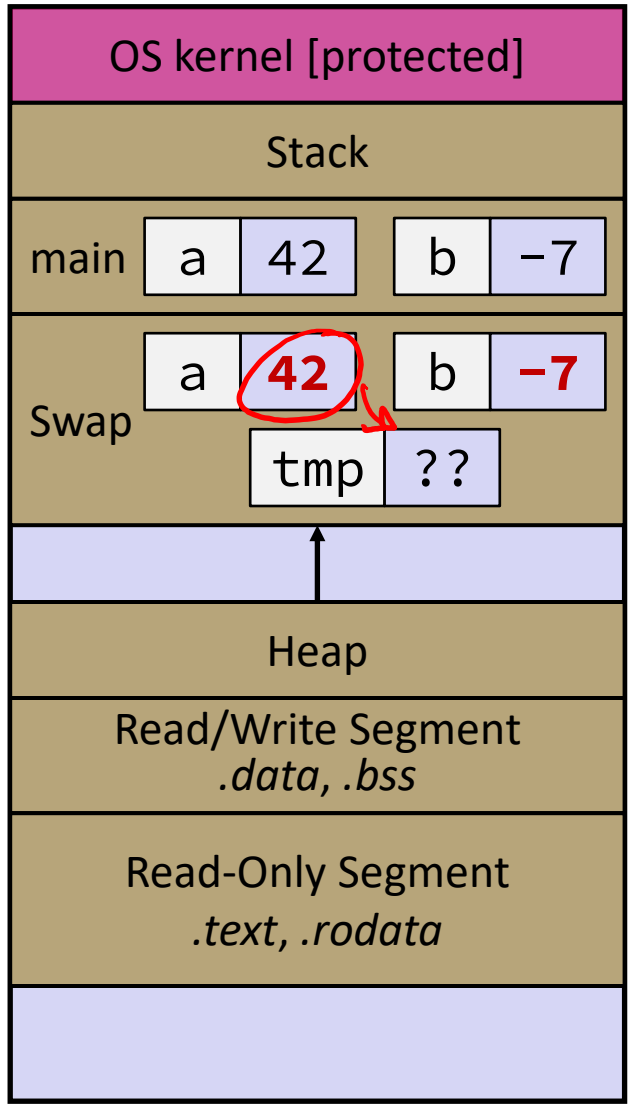
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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



Broken Swap (3/7)

brokenswap.c

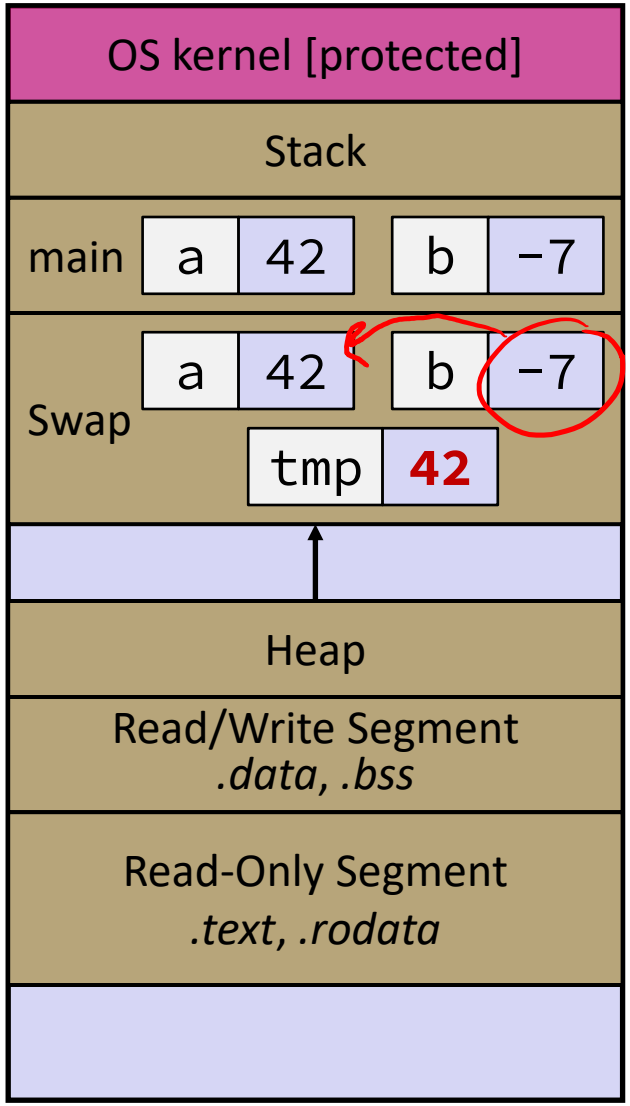
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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



Broken Swap (4/7)

brokenswap.c

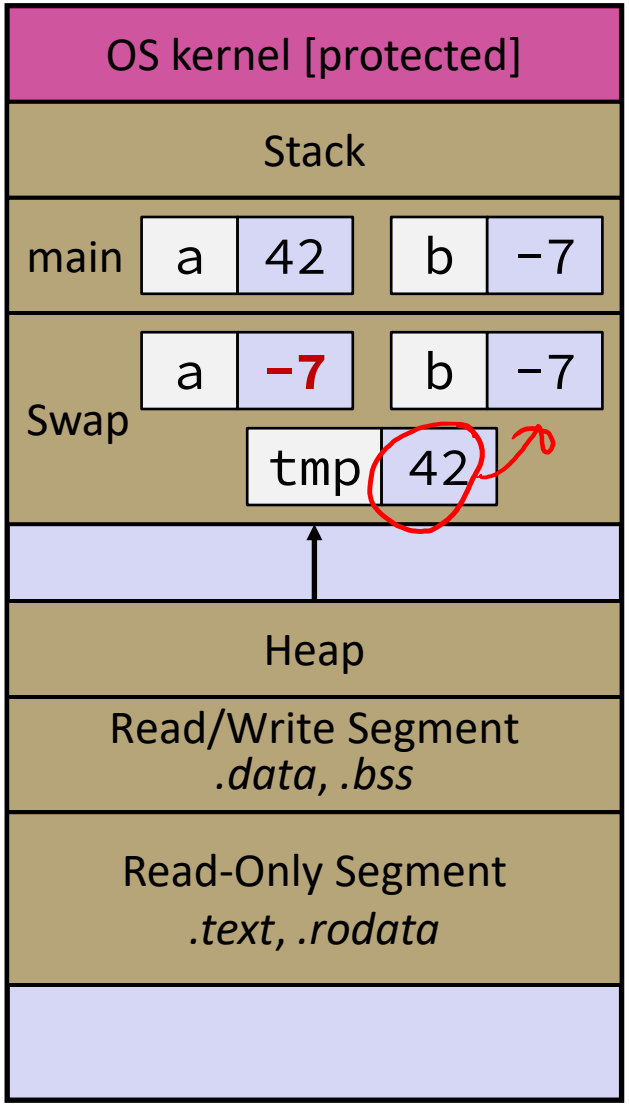
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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



Broken Swap (5/7)

brokenswap.c

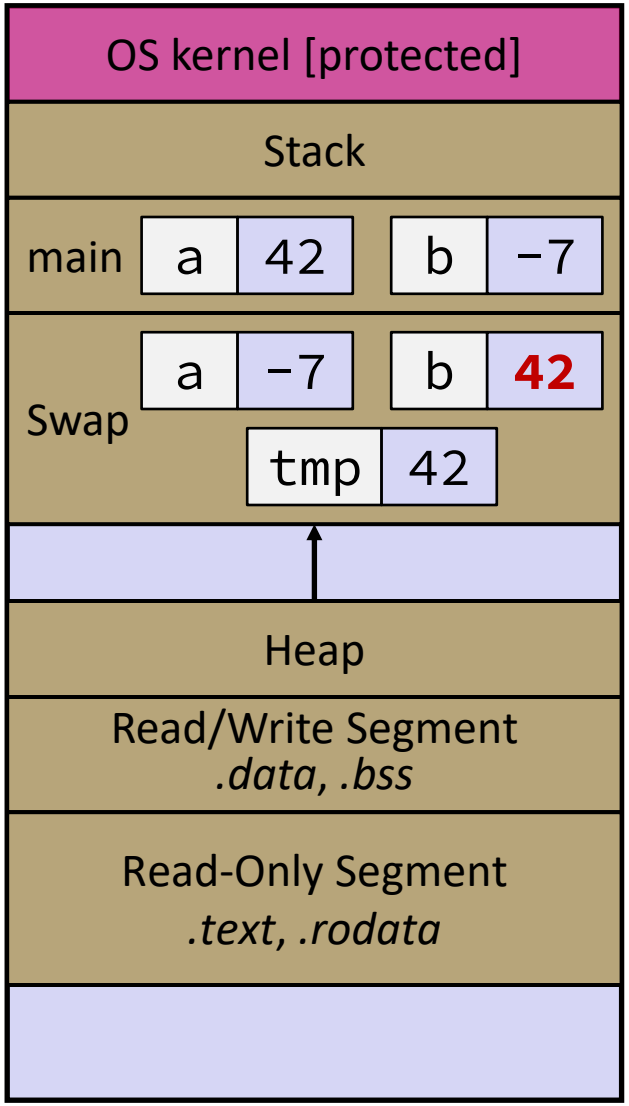
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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



Broken Swap (6/7)

brokenswap.c

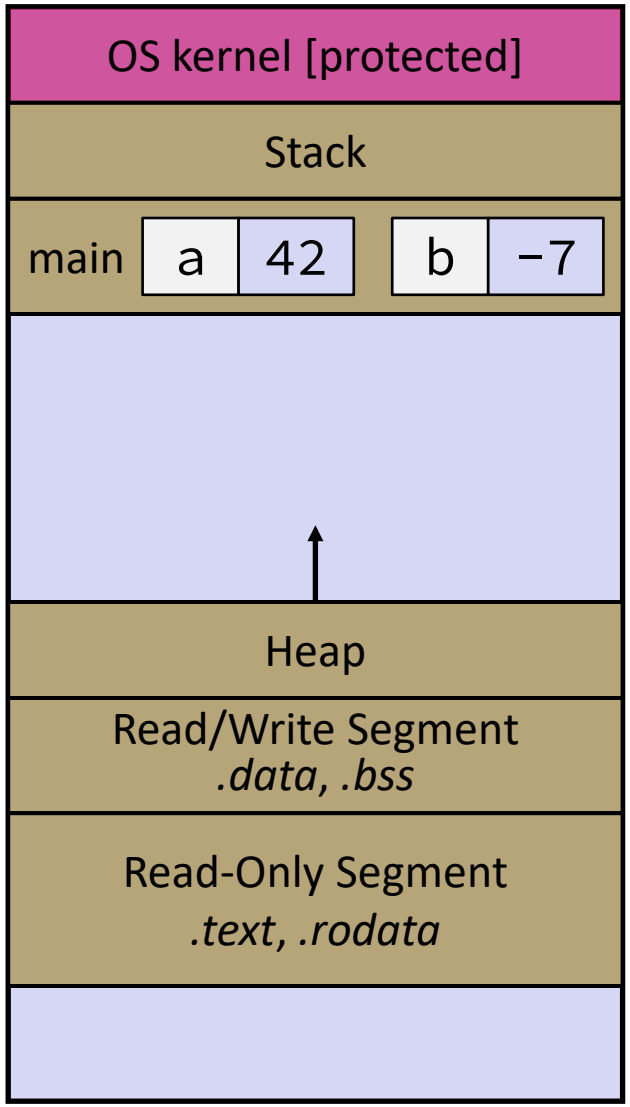
```
void Swap(int a, int b) {
  int tmp = a;
  a = b;
  b = tmp;
}

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



Broken Swap (7/7)

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);
  ...
```



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

a_ptr b_ptr

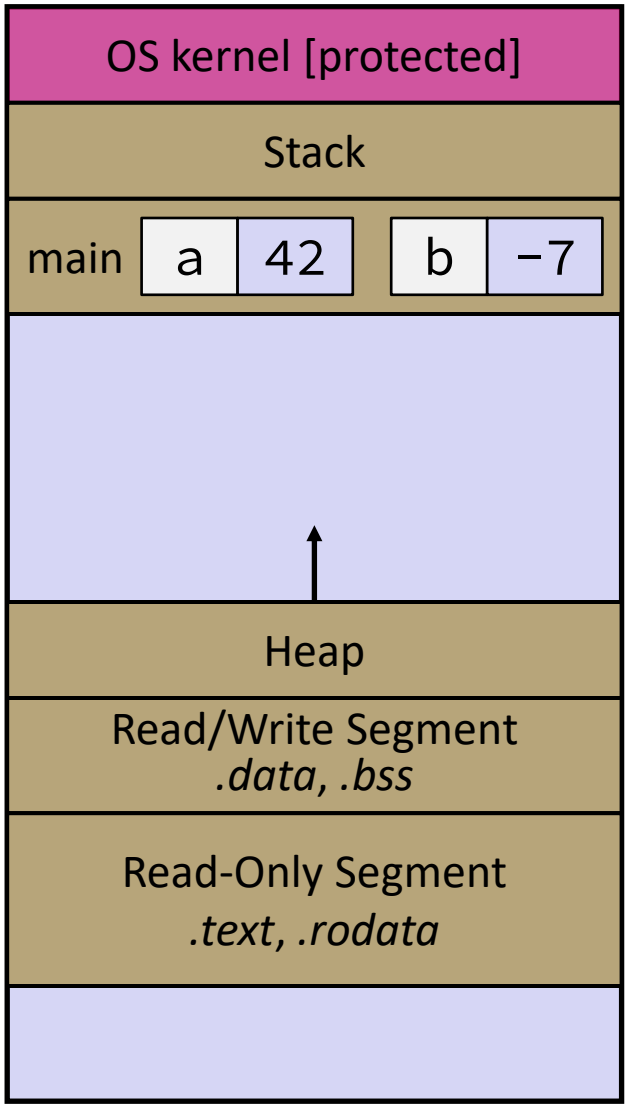
```
void Swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

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

Fixed Swap (1/6)

Note: Arrow points to *next* instruction.

swap.c

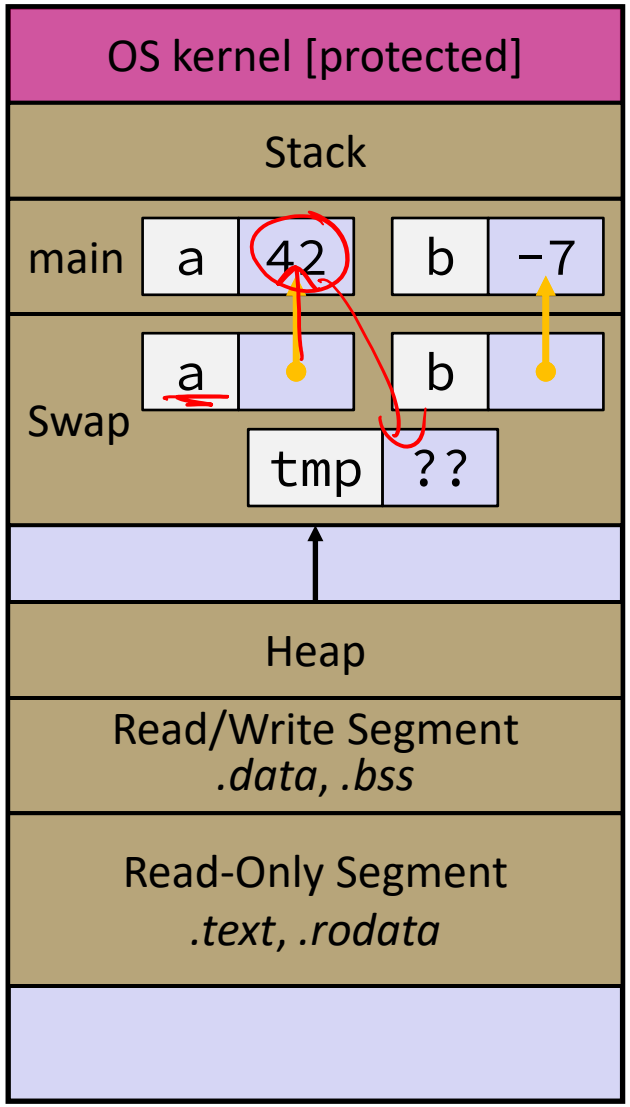
```
void Swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

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



Fixed Swap (2/6)

swap.c

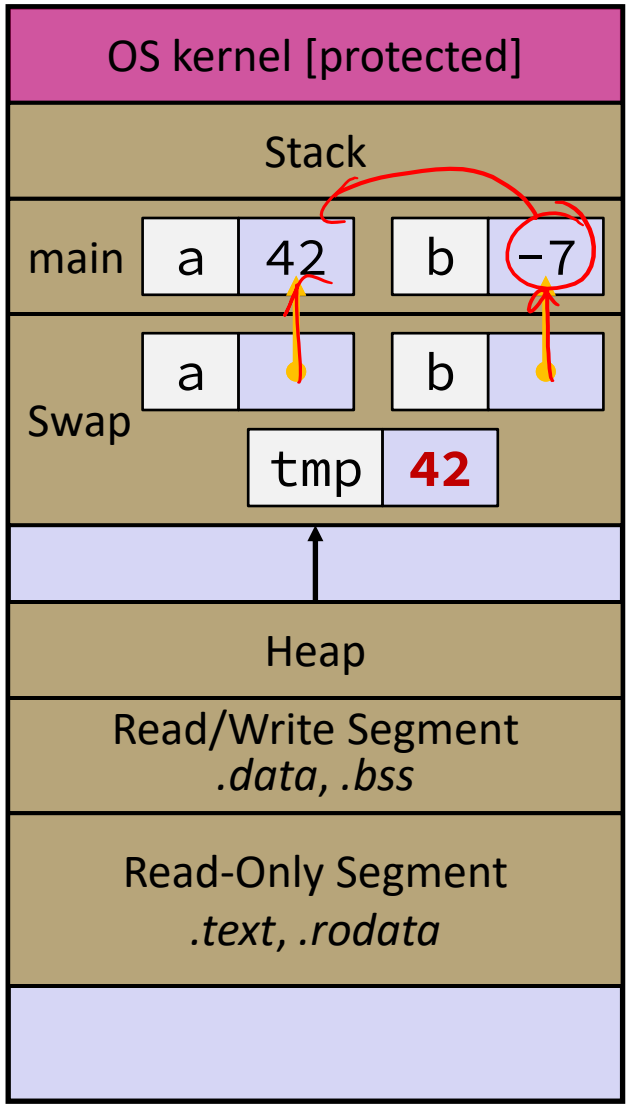
```
void Swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

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



Fixed Swap (3/6)

swap.c

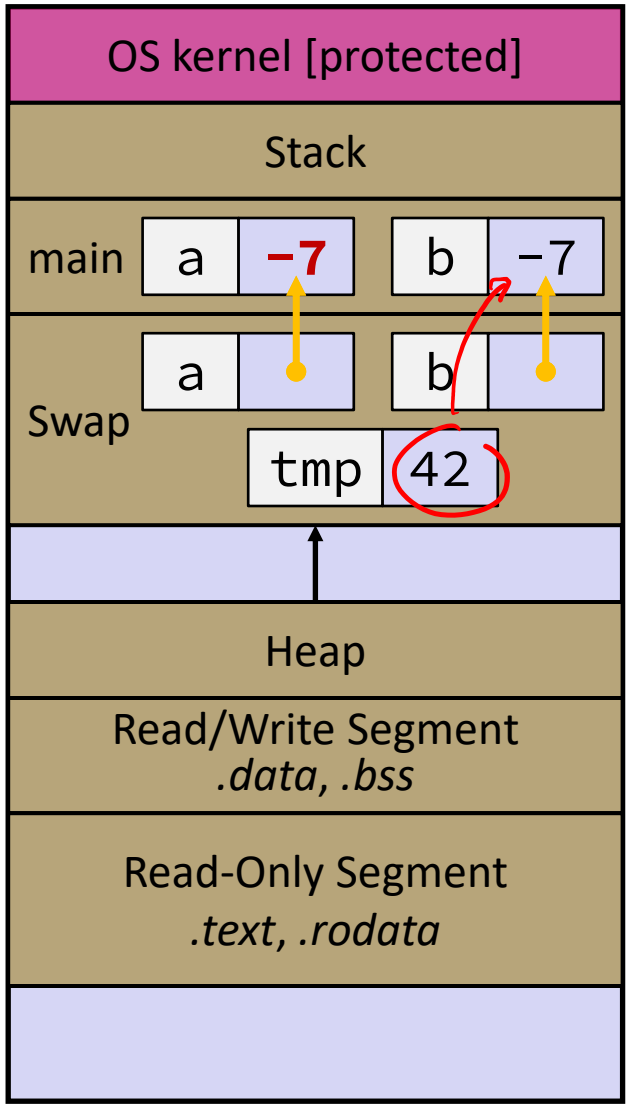
```
void Swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

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



Fixed Swap (4/6)

swap.c

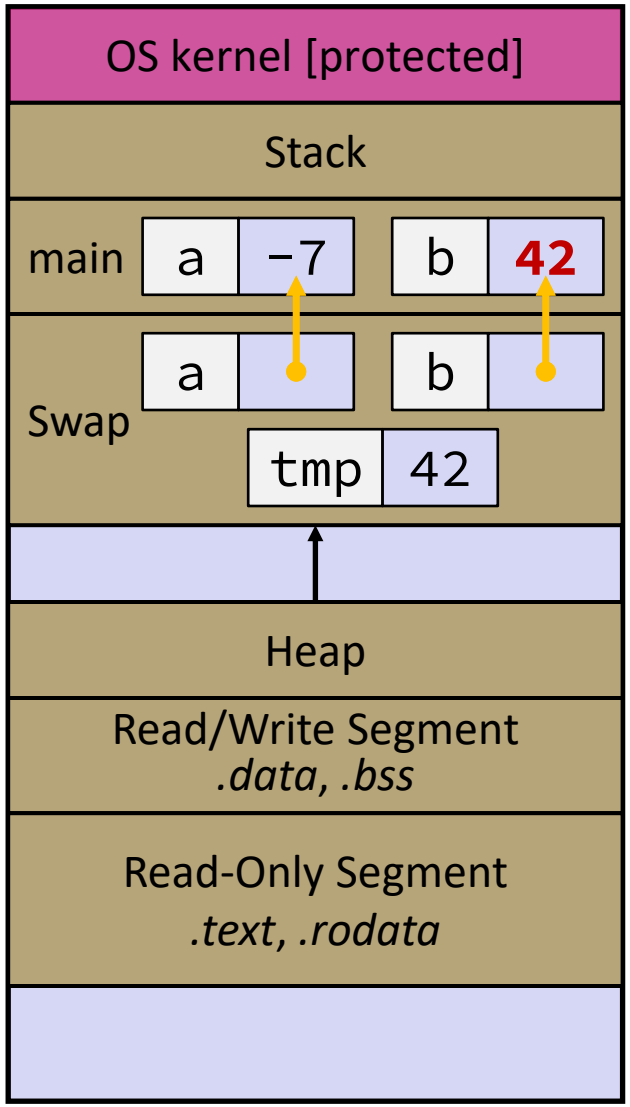
```
void Swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

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



Fixed Swap (5/6)

swap.c

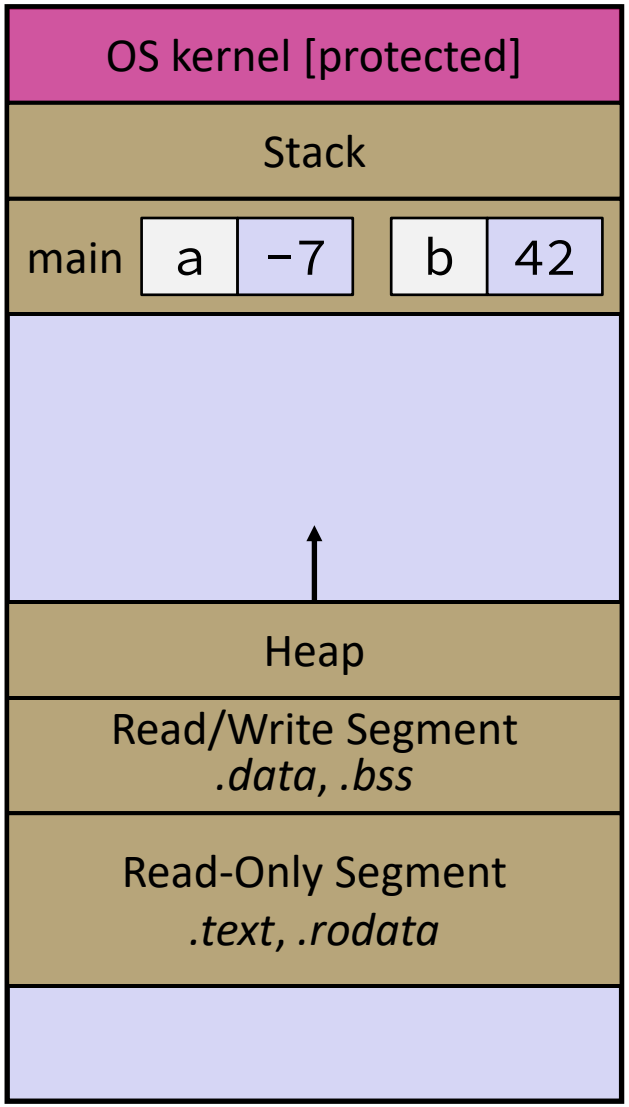
```
void Swap(int* a, int* b) {
  int tmp = *a;
  *a = *b;
  *b = tmp;
}

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



Fixed Swap (6/6)

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);
  ...
```



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

pollev.com/cse333j

Which of the following are *invalid* ways 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);
```

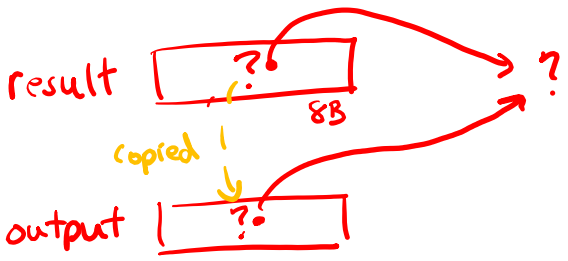
E. We're lost…

Which of the following are *invalid* ways to invoke `GenerateString()`?

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

A.

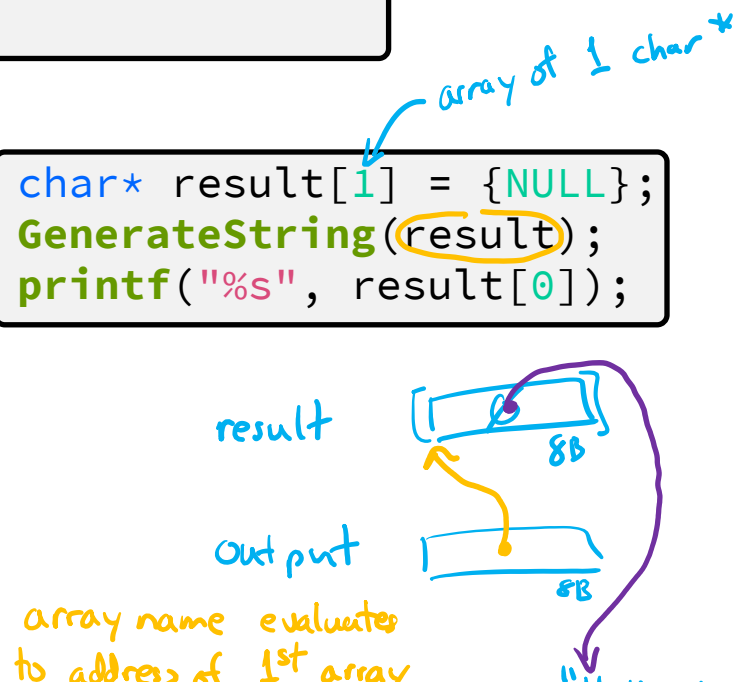
```
char** result; //uninitialized!
GenerateString(result);
printf("%s", *result);
```



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

C.

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



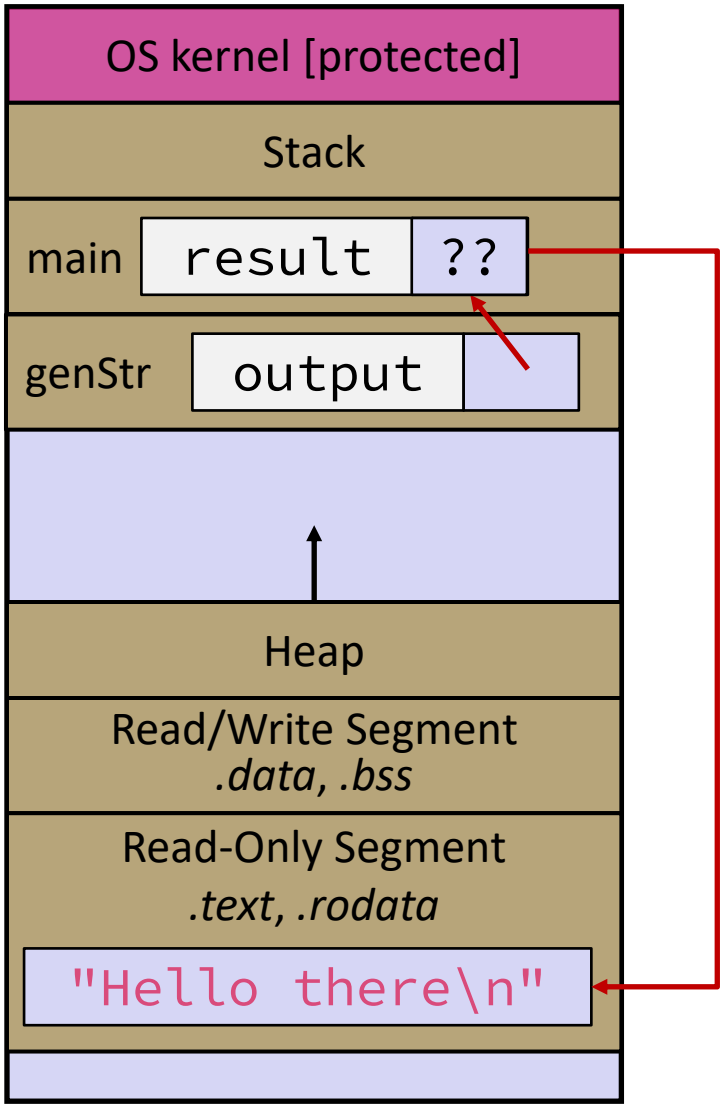
array name evaluates to address of 1st array element (char**)

dereferencing output lets us update result[0]

Preferred Usage

Note: Arrow points to *next* instruction.

genstr.c



D.

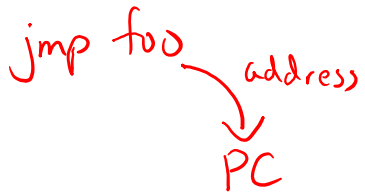
```
void GenerateString(char** output);

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)

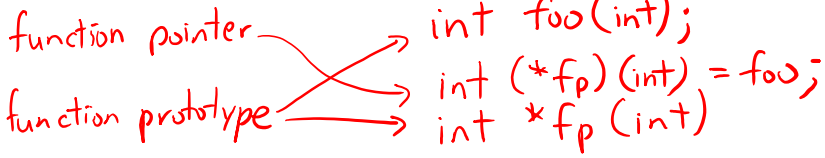
Lecture Outline (4/4)

- Pointer Basics
- Pointer Arithmetic
- Pointers as Parameters
- **Function Pointers**

Function Pointers



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



- 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

- Using the function: dereference

```
(*name)(arg1, …, argN)
```

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

Function Pointer Example (1/2)

- 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 (2/2)

- 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

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