Pointers, Pointers, Pointers
CSE 333

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Poll Everywhere

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- Consider our example `pointy.c` from last lecture

- Which segment of memory is `x` allocated in? How many bytes of storage does it use? How many bytes does `p` use?

```
int main(int argc, char** argv) {
  int x = 351;
  int* p;      // p is a pointer to a int

  p = &x;      // p now contains the addr of x

  // ...

  return 0;
}
```

pointy.c

Administrivia (1)

- Office hours started today! See schedule on web calendar

- Discussion board: prefer public postings to private
  - … unless it has specific code or other details that should not be shared.
  - Then the answers can help more people and we can reduce duplicate effort to answer the same question(s) multiple times.
  - Anonymous postings are fine if you're feeling bashful. ☺

- Exercises
  - ex0 was due this morning; ex1 is due on Wednesday morning
  - You can expect the pace to pick up from now on
- Homeworks
  - hw0 due tomorrow night
  - hw1's spec and starter code will be out by Wednesday(ish)

Administrivia (2)

- Homework 1 is the first "meaty" homework of our series
  - Linked list and hash table implementations in C
  - Read the spec and start poking around the code *before* Thursday section
  - For large projects, you must pace yourself! If something baffling happens:
    - You can let it go for the day and come back to it tomorrow
    - You can ask for help from peers or staff

Administrivia (3)

- Time management data:
  - Exercises will be assigned almost every lecture until early November
  - Median completion time was 1.5-2 hours in 24sp (depending on the specific exercise

  - You have ~13d to complete HW1
  - Median completion time in 24sp was 14h

- Budget your time accordingly!

Poll Everywhere

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- Please fill in timing stats for HW0 and Ex1

- No conceptual warmup question today
- Instead, review slides from last week (Wed + Fri) about structs
  - Any questions?

Administrivia, Day 2

- Another exercise, ex2 releases today
  - Get used to this pace!
- HW1 starter code coming out soon
- Use gitlab add/commit/push *regularly* after a chunk is done to save work (*not* just once at the end of the project – gitlab is not a "turnin server", it's a code repository)
  - Especially after each new part of the project or other unit of work is done
  - Provides backup in case later work clobbers useful things or computer crashes or …

Lecture Outline

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

Pointers

- Variables that store addresses
- Generic definition: `type* name;` or `type *name;`

- *Dereference* a pointer using the unary `*` operator
- *Get the address* of variable `foo` using the unary `&` operator

Box-and-Arrow Diagrams

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

Box-and-Arrow Diagrams

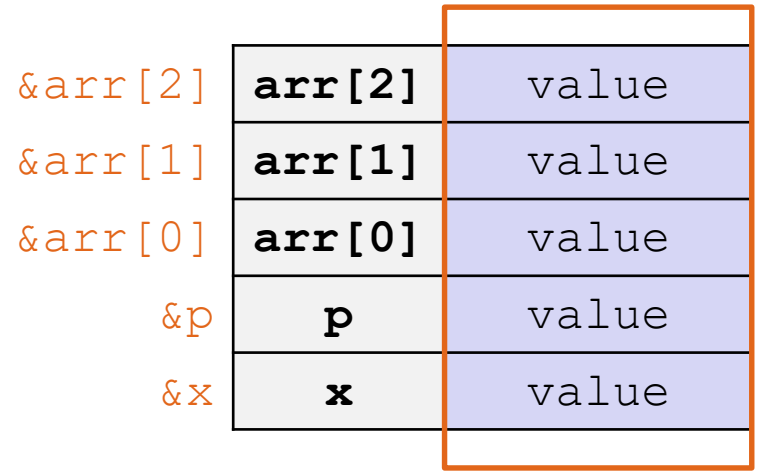
boxarrow.c

```
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



Box-and-Arrow Diagrams

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

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

Box-and-Arrow Diagrams

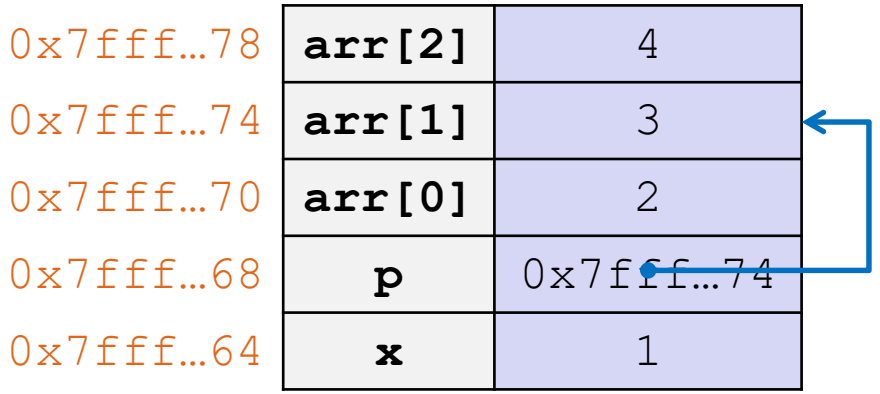
boxarrow.c

```
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



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 and a pointer
  - Subtract two pointers (within same stack frame or malloc block)
  - Compare pointers (<, <=, ==, !=, >, >=), including `NULL`

Inadvisable Pointer Examples 

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

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

"Pointers are variables that contain addresses"

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

inadvisable_pointers.c

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

"Pointers are variables that contain addresses"

Since pointers are *also* variables, we can do all these horrible things recursively

Poll Everywhere

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- What is the state of arr[]?

boxarrow2.c

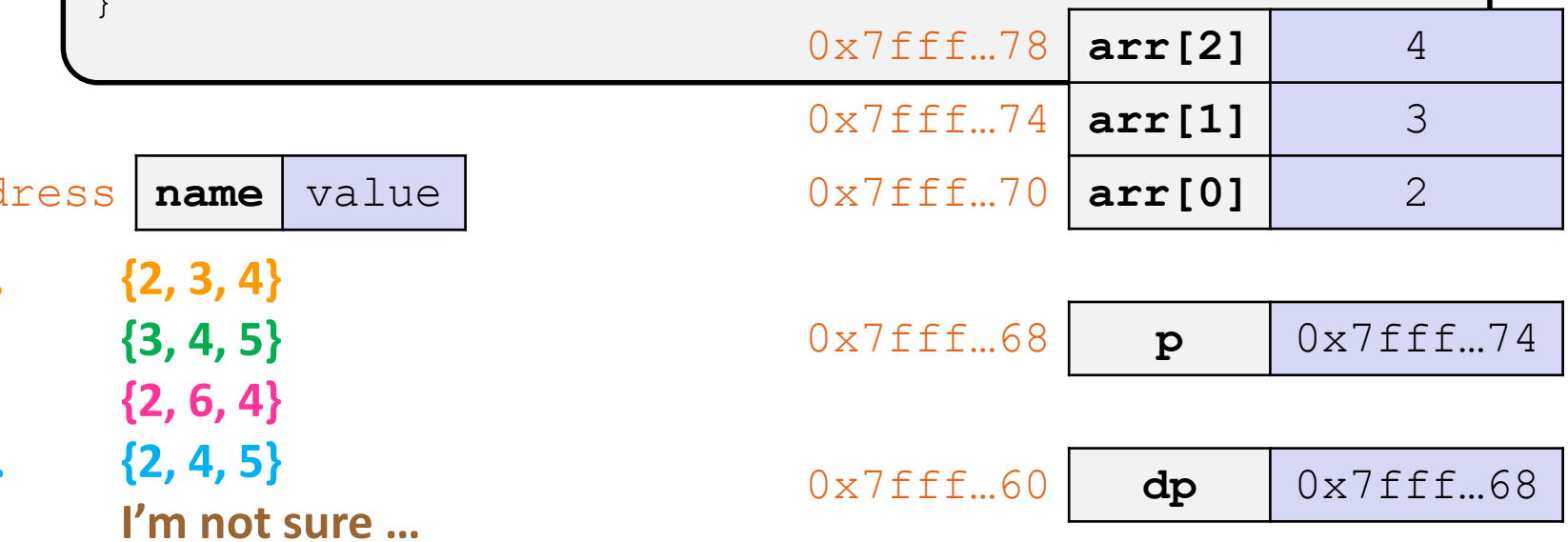
```
int main(int argc, char** argv) {
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];
  int** dp = &p;  // pointer to a pointer

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

  return EXIT_SUCCESS;
}
```

address	name	value

A. {2, 3, 4}
B. {3, 4, 5}
C. {2, 6, 4}
D. {2, 4, 5}
E. I'm not sure …



Practice Solution

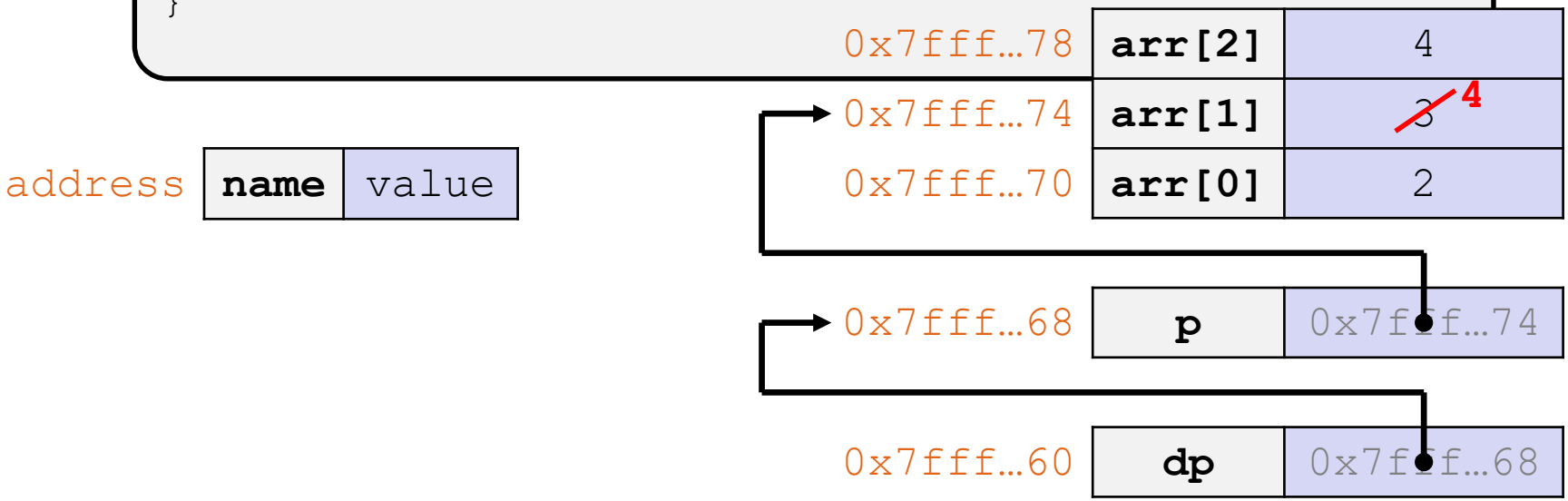
Note: arrow points to *next* instruction to be executed.

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;
}
```



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boxarrow2.c

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  int arr[3] = {2, 3, 4};
  int* p = &arr[1];
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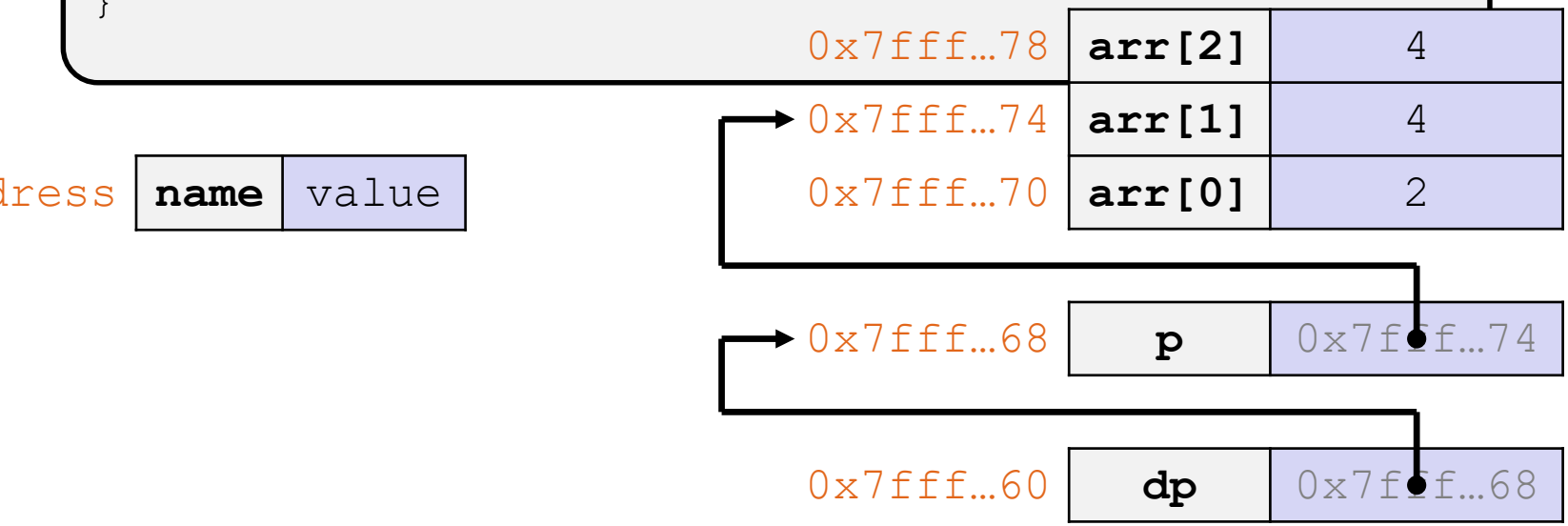
  *(*dp) += 1;
  p += 1;
  *(*dp) += 1;

  return EXIT_SUCCESS;
}
```



address	name	value

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boxarrow2.c

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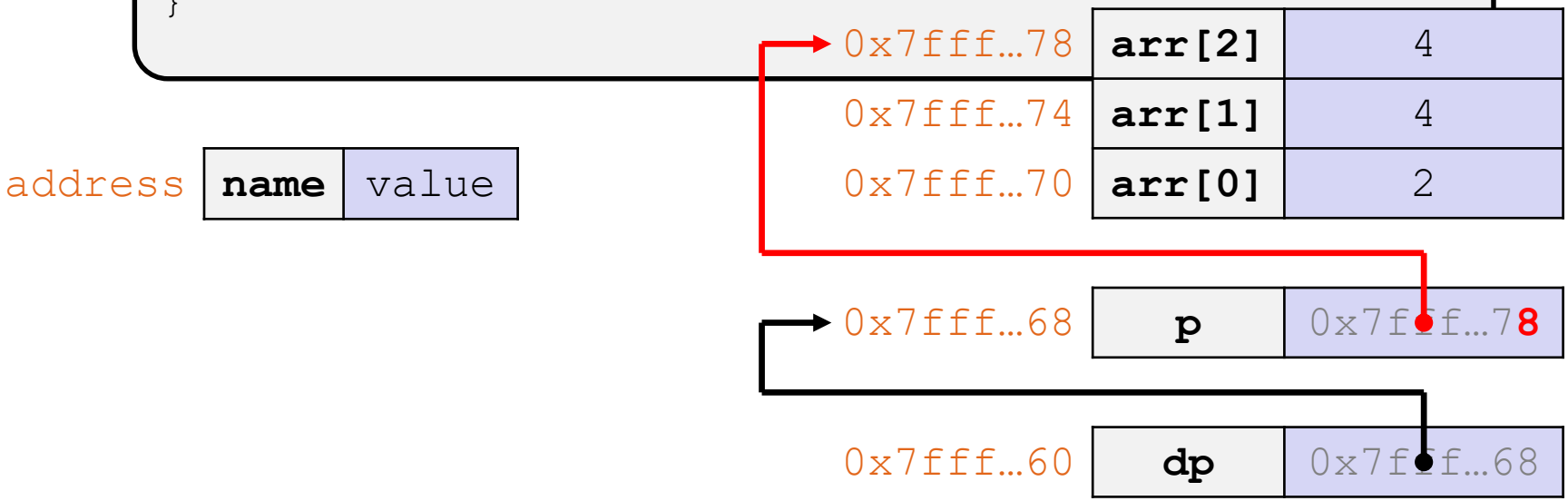
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];
  int** dp = &p;  // pointer to a pointer

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

  return EXIT_SUCCESS;
}
```



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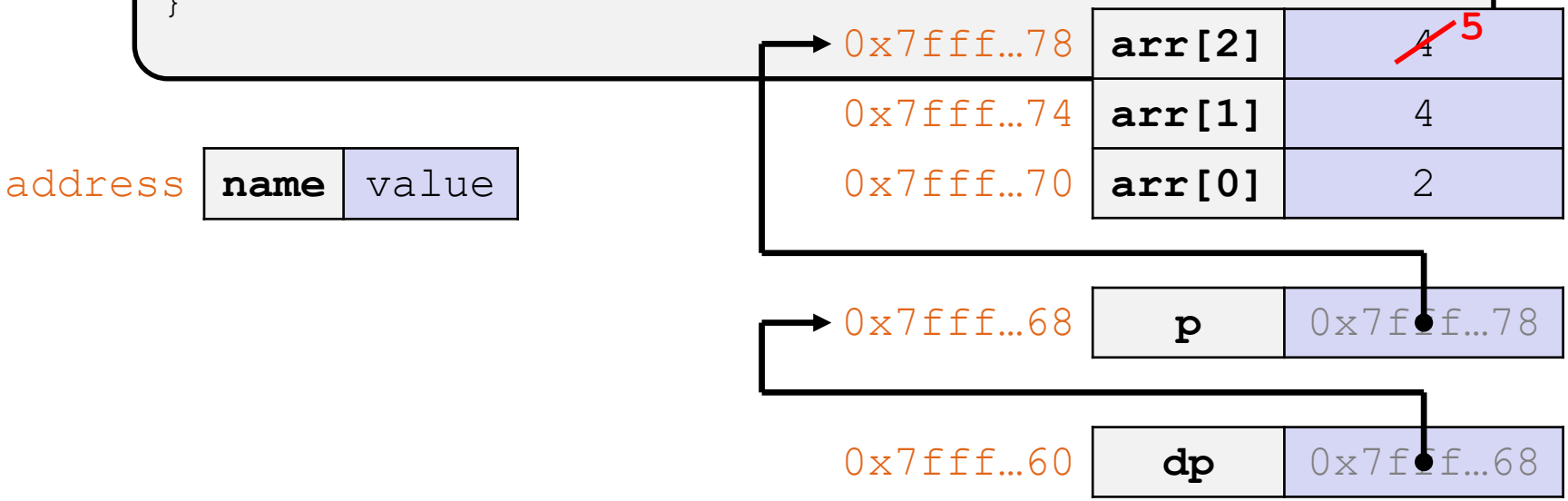
boxarrow2.c

```
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;

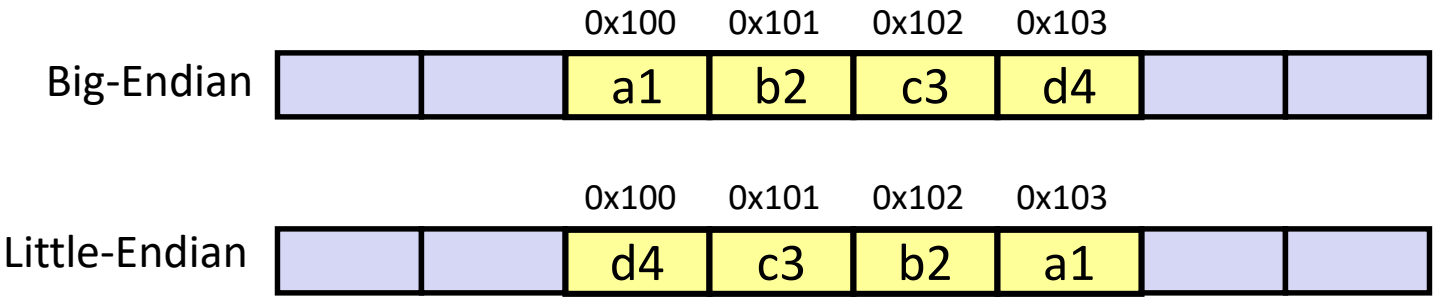
  return EXIT_SUCCESS;
}
```



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* address
  - Little-endian: Least significant byte has *lowest* address

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



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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 = 4;
  int_ptr += 2;  // uh oh

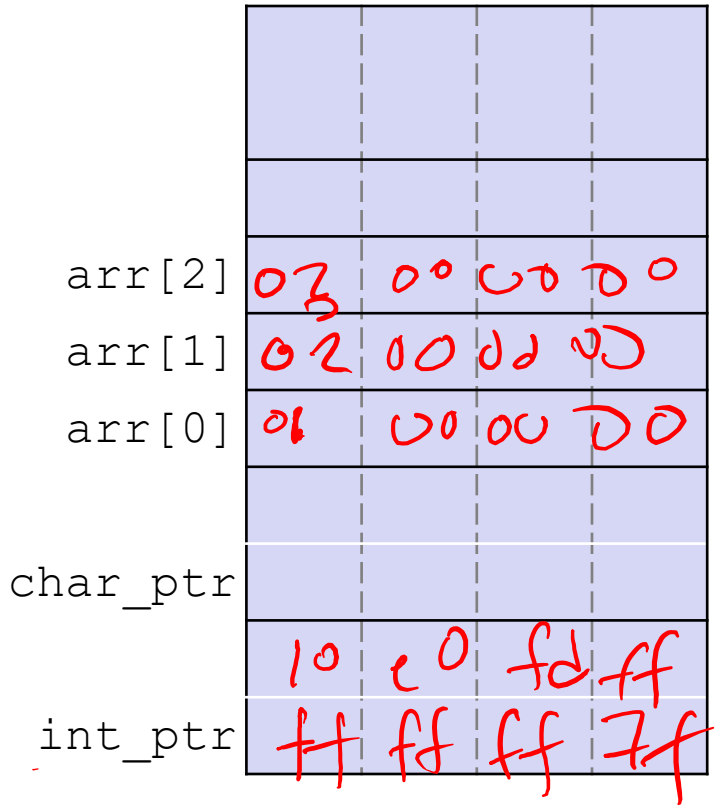
  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c

Note: Arrow points to *next* instruction.

Stack (assume x86-64)



What is the state of the stack?

You can assume the address of the stack's base is `0x7fffffffffde000`

Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

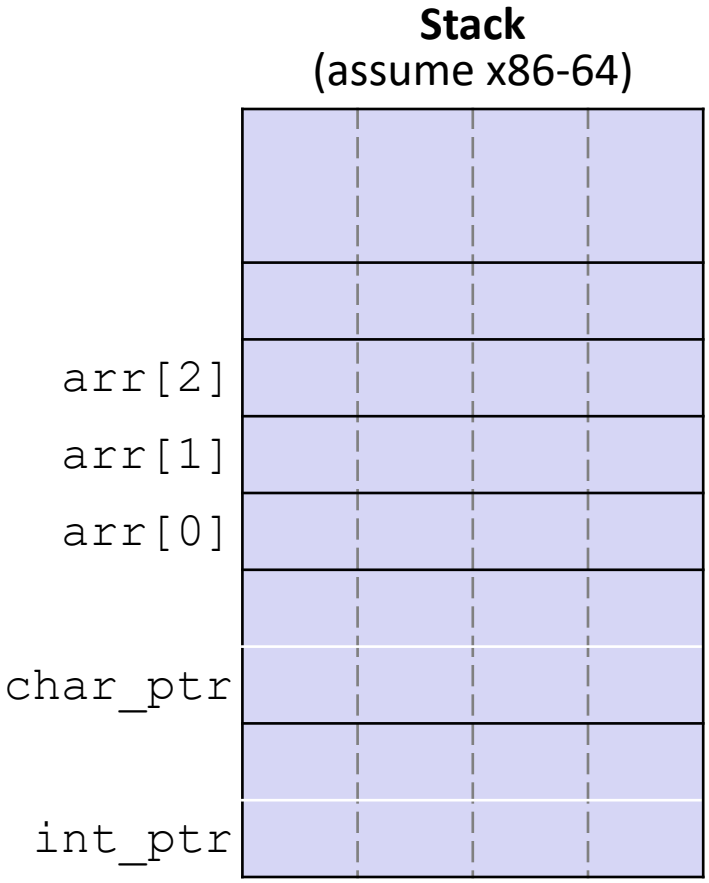
```
int main(int argc, char** argv) {
  int arr[3] = {1, 2, 3};
  int* int_ptr = &arr[0];
  char* char_ptr = (char*) int_ptr;

  int_ptr += 1;
  *int_ptr = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c



Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

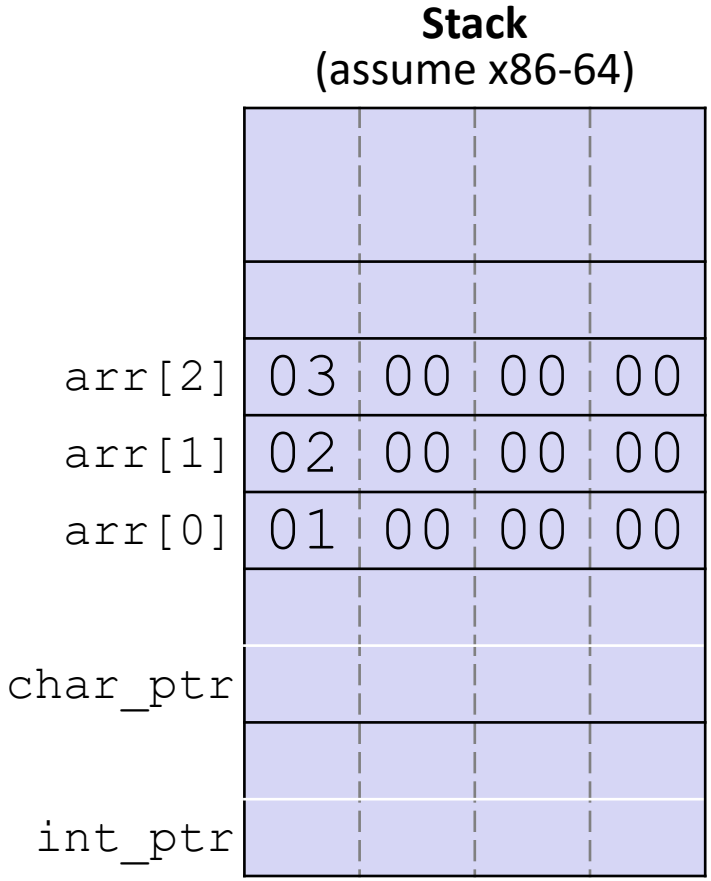
```
int main(int argc, char** argv) {
  int arr[3] = {1, 2, 3};
  int* int_ptr = &arr[0];
  char* char_ptr = (char*) int_ptr;

  int_ptr += 1;
  *int_ptr = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c



Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

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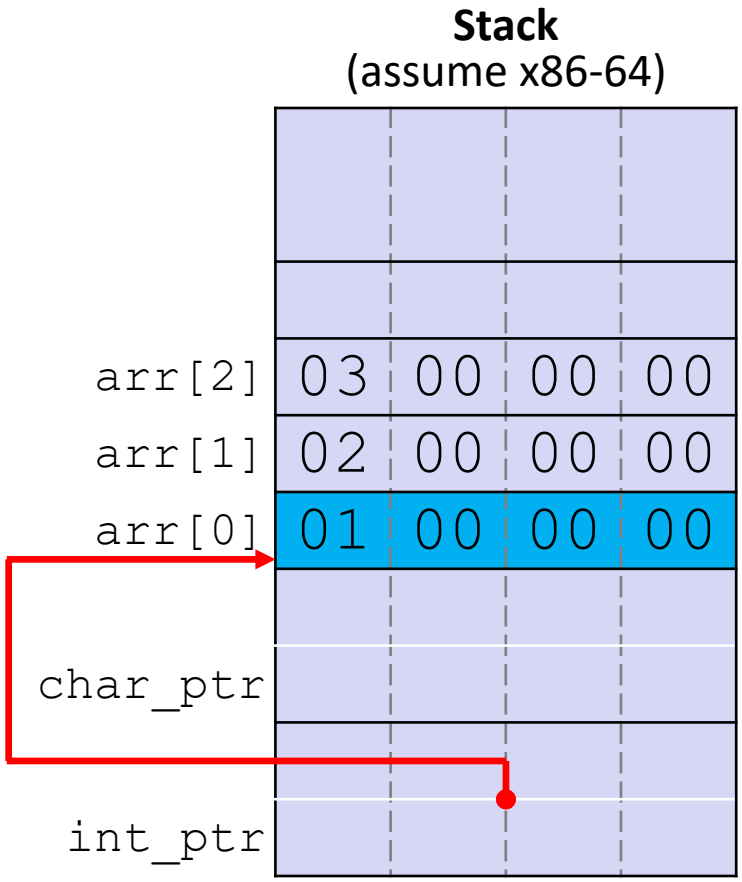
  int arr[3] = {1, 2, 3};
  int* int_ptr = &arr[0];
  char* char_ptr = (char*) int_ptr;

  int_ptr += 1;
  *int_ptr = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

pointerarithmetic.c



Pointer Arithmetic Example

Note: Arrow points to *next* instruction.

```
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  int arr[3] = {1, 2, 3};
  int* int_ptr = &arr[0];
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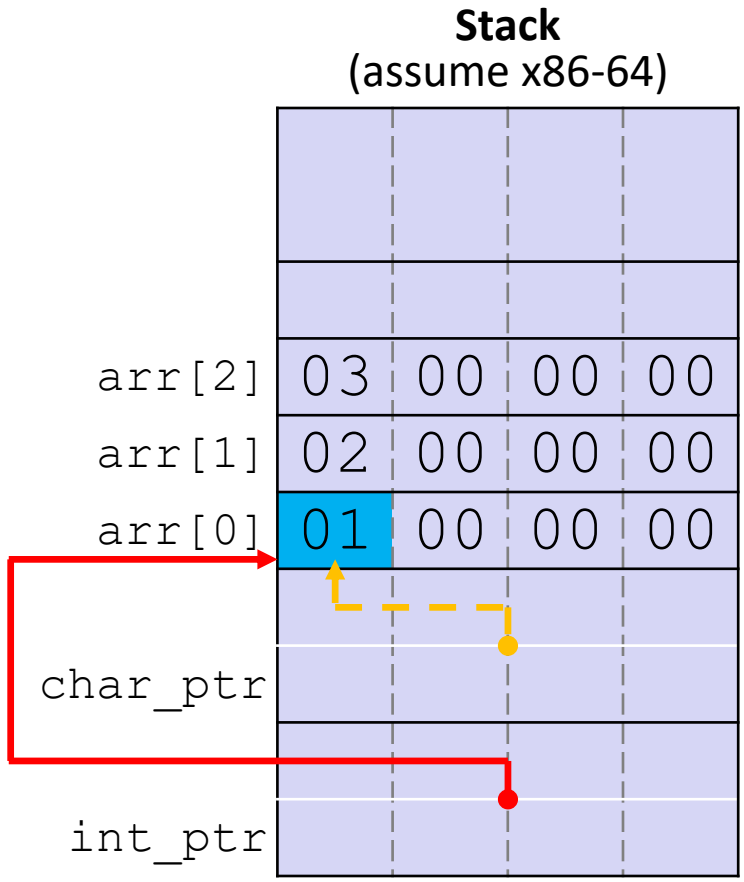
  int_ptr += 1;
  *int_ptr = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```

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;
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  int_ptr += 2;  // uh oh

  char_ptr += 1;
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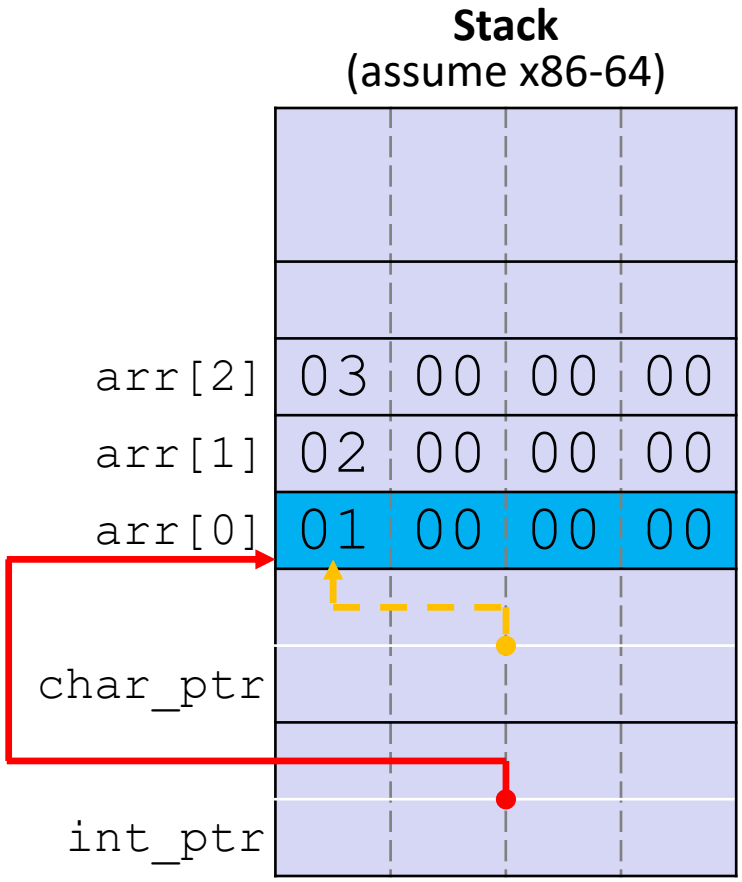
  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

```
 int_ptr:   0x7fffffffffde010
*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;
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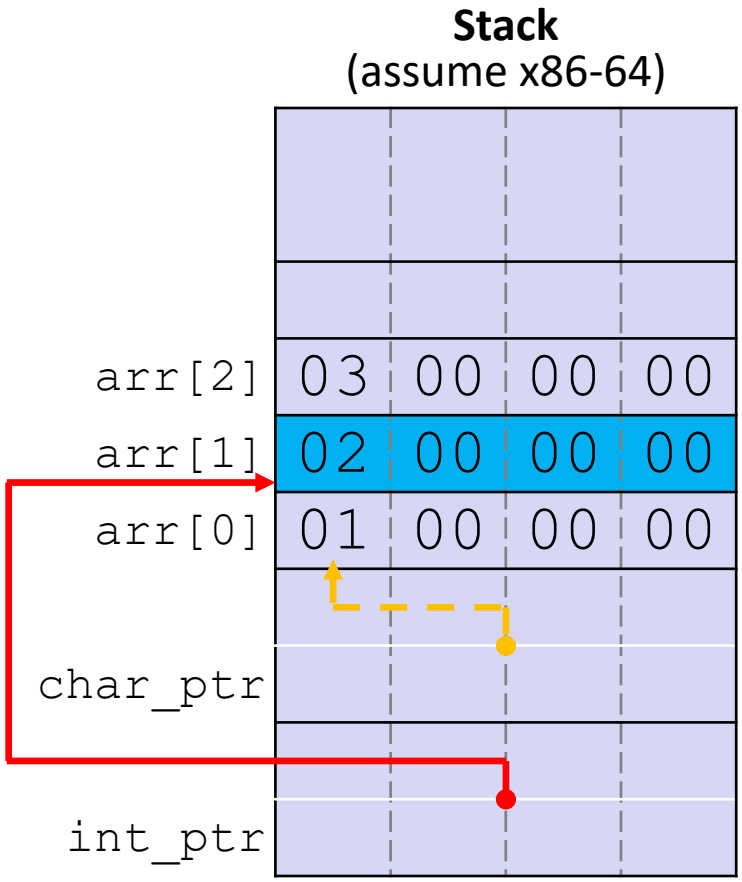
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

int_ptr: 0x7ffffffffde014
***int_ptr:** 0

Pointer Arithmetic Example

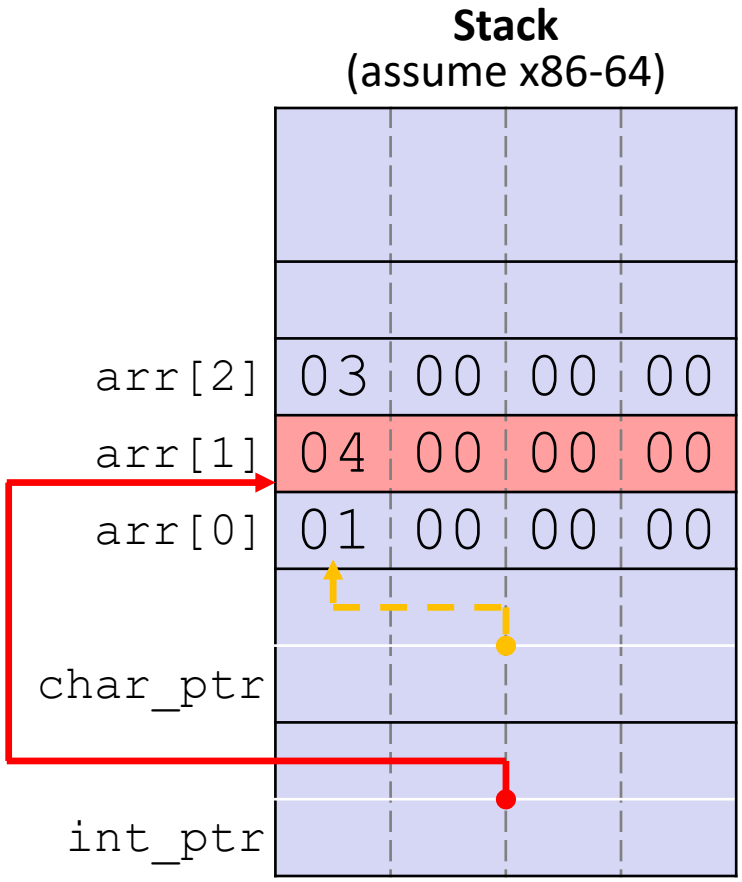
Note: Arrow points to *next* instruction.

```
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 = 4;
  int_ptr += 2;   // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

```
 int_ptr:   0x7fffffffffde014
*int_ptr:   4
```

Pointer Arithmetic Example

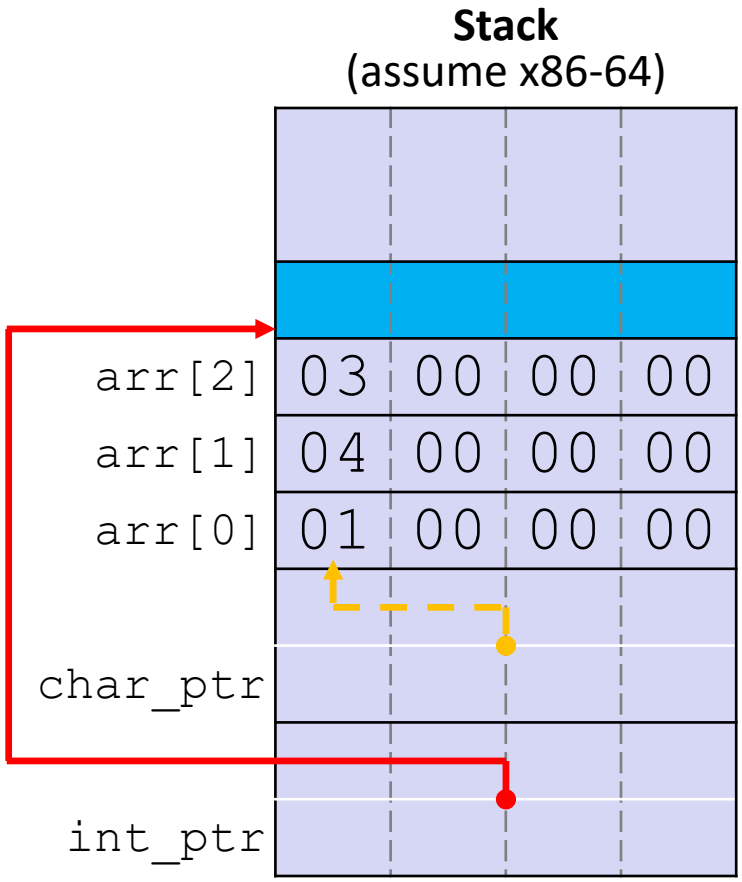
Note: Arrow points to *next* instruction.

```
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 = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

int_ptr: 0x7fffffffffde01**c**

***int_ptr:** **???**

Pointer Arithmetic Example

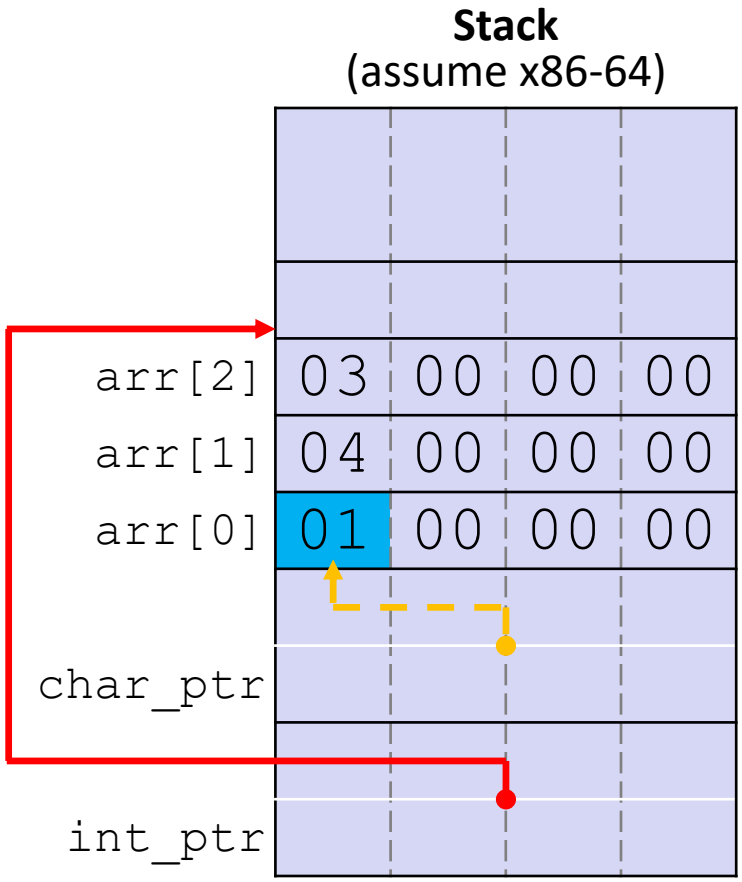
Note: Arrow points to *next* instruction.

```
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 = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

```
 char_ptr:   0x7fffffffffde010
*char_ptr:   1
```

Pointer Arithmetic Example

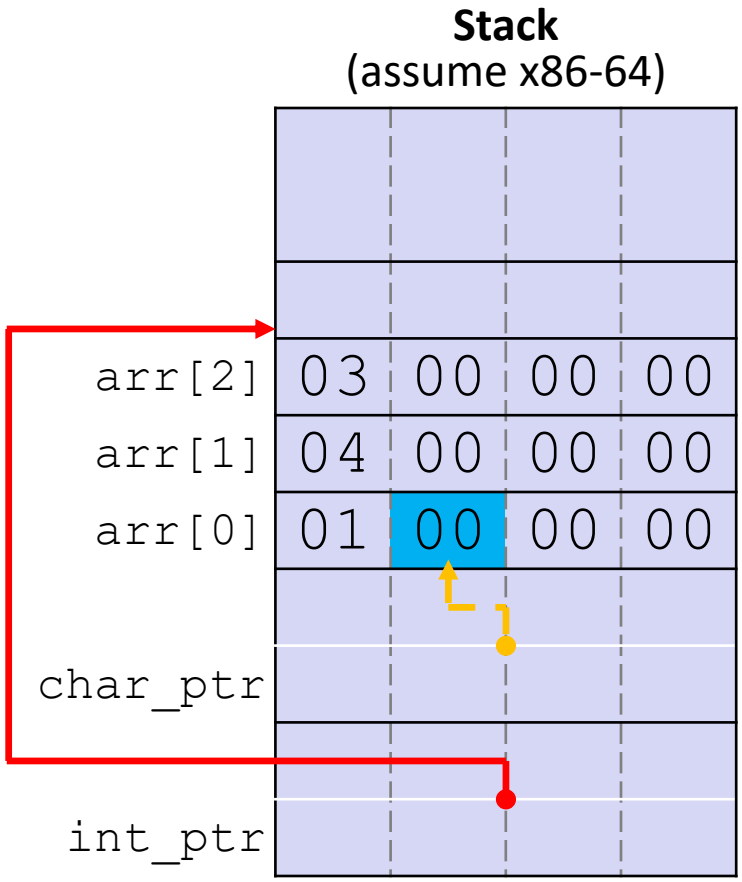
Note: Arrow points to *next* instruction.

```
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 = 4;
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

char_ptr: 0x7fffffffffde011
***char_ptr:** 0

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;
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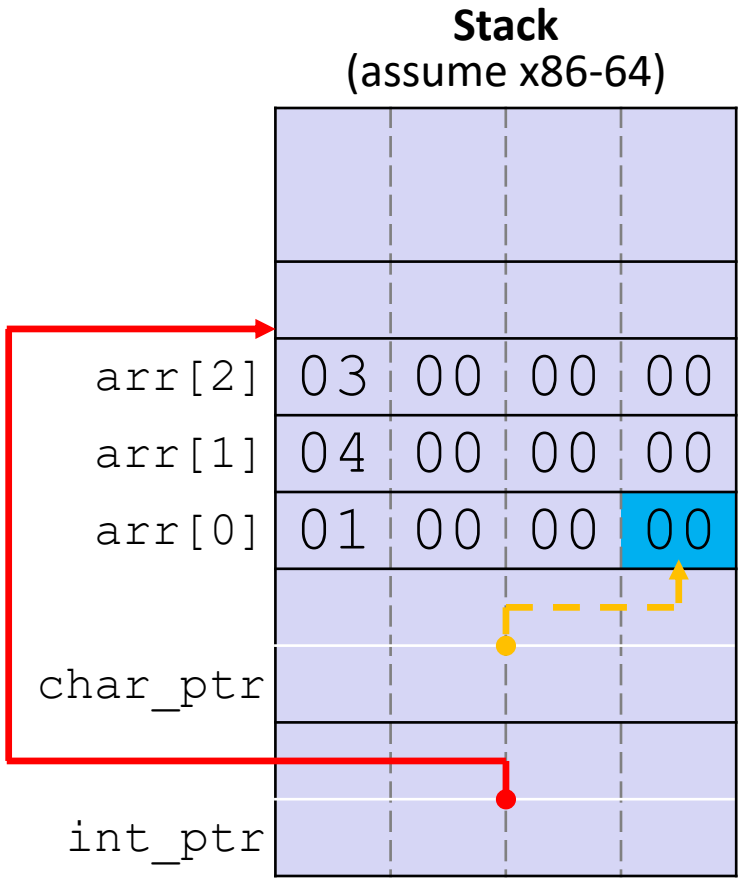
  int_ptr += 2;  // uh oh

  char_ptr += 1;
  char_ptr += 2;

  return EXIT_SUCCESS;
}
```



pointerarithmetic.c

char_ptr: 0x7fffffffffde013
***char_ptr:** 0

Lecture Outline

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

C parameters are 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);
  ...
```

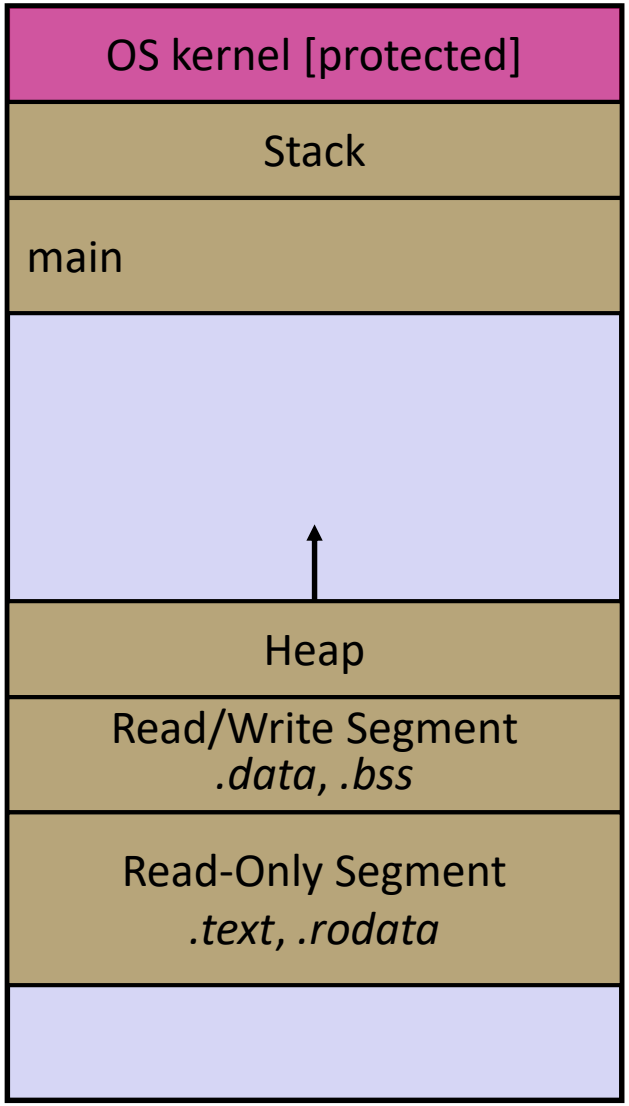
Broken Swap

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);
  ...
```

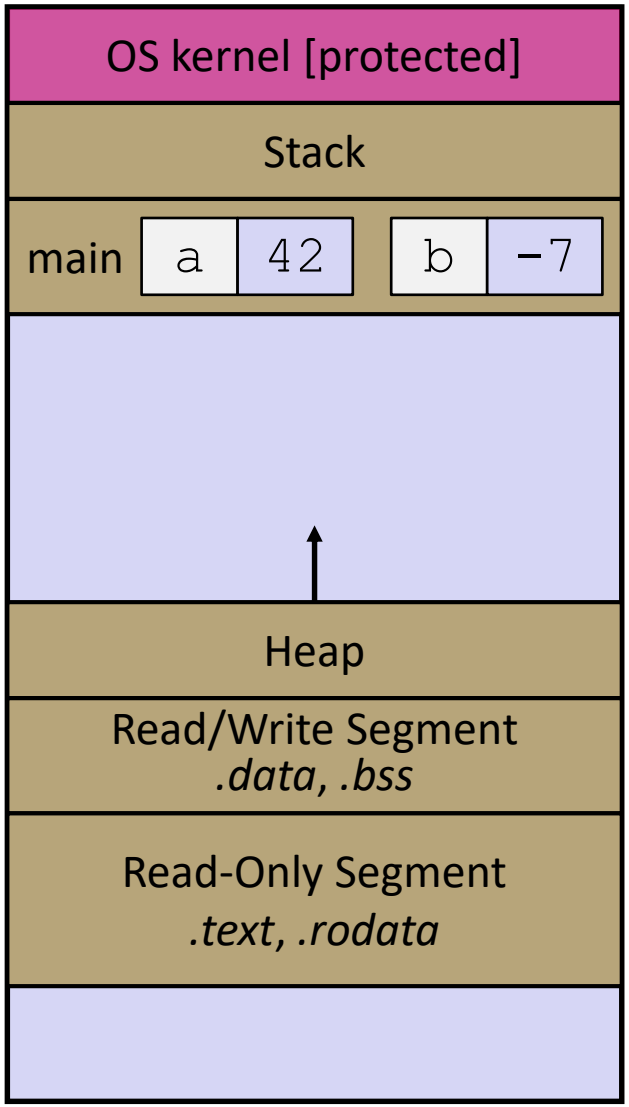


Broken Swap

brokenswap.c

```
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

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

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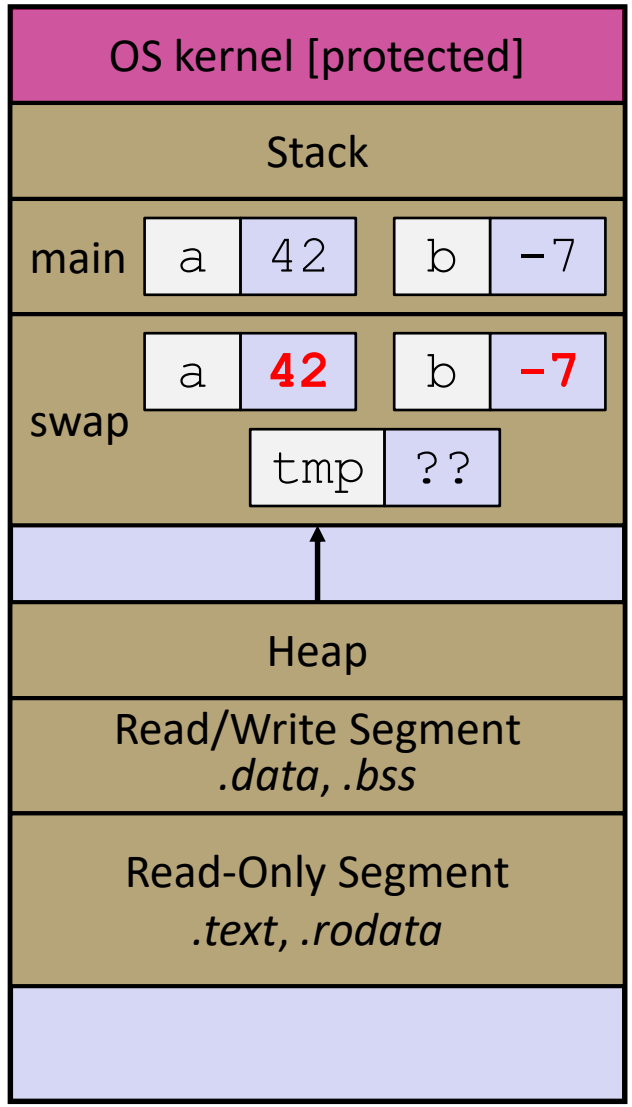

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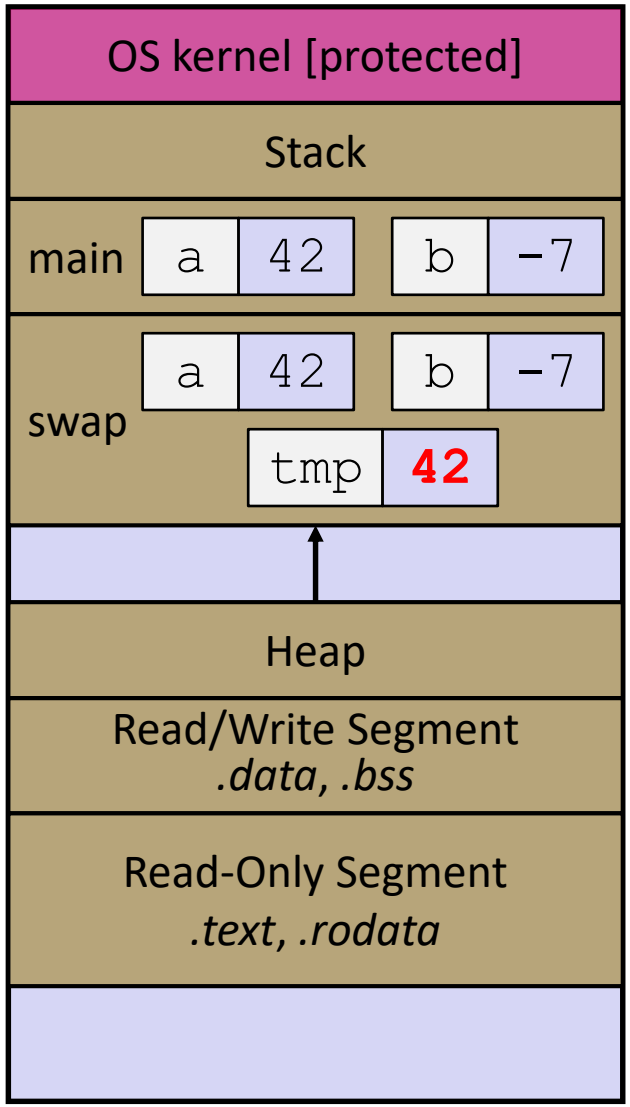

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  int tmp = a;
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  swap(a, b);
  ...
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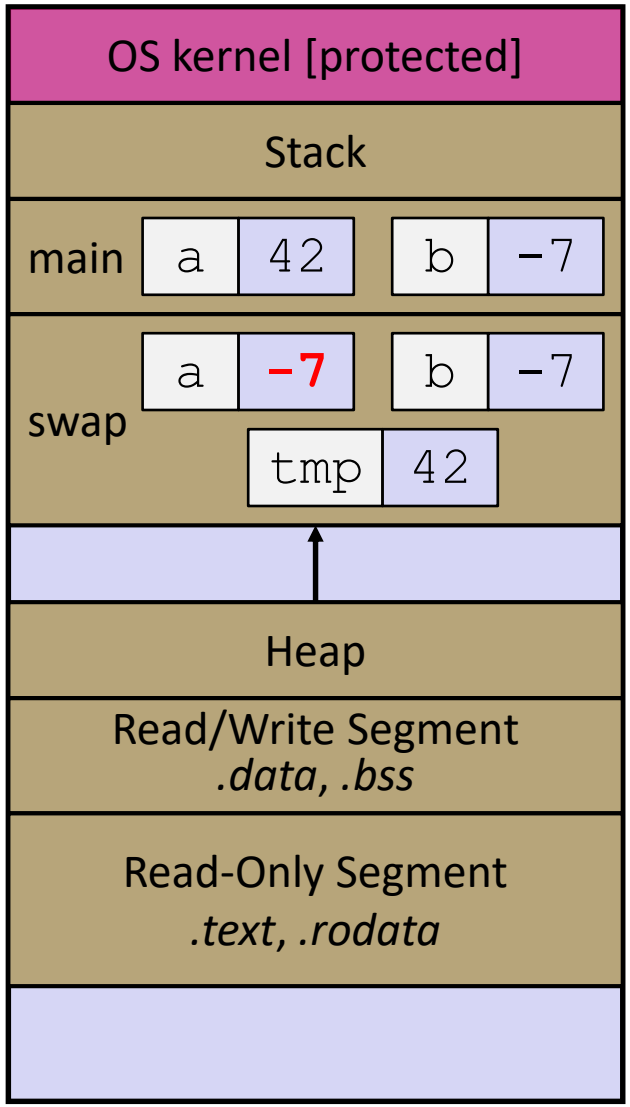

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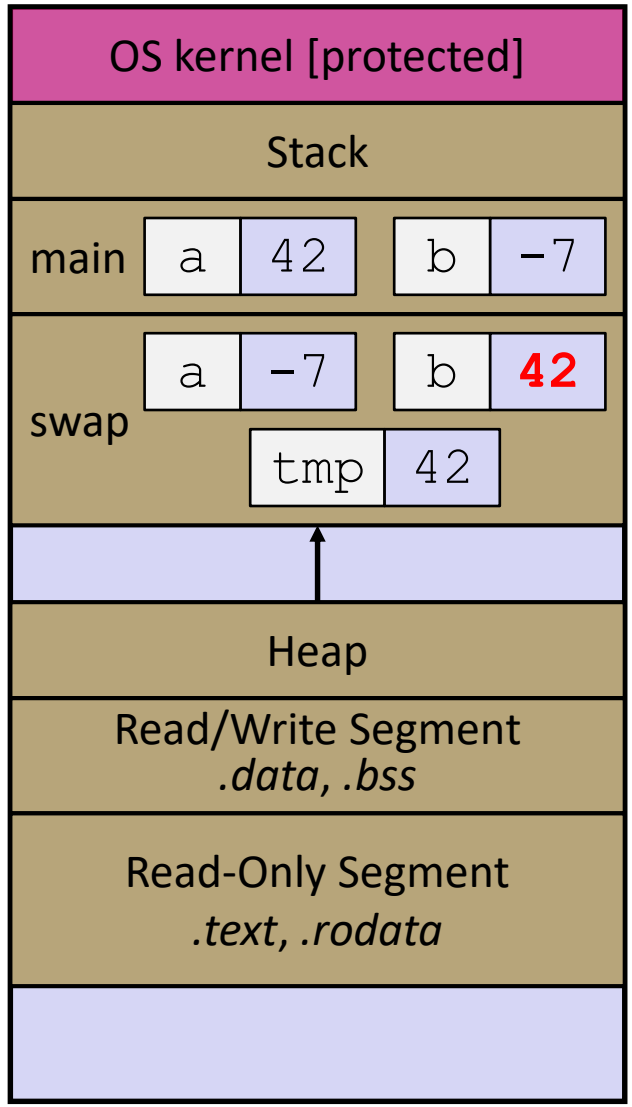

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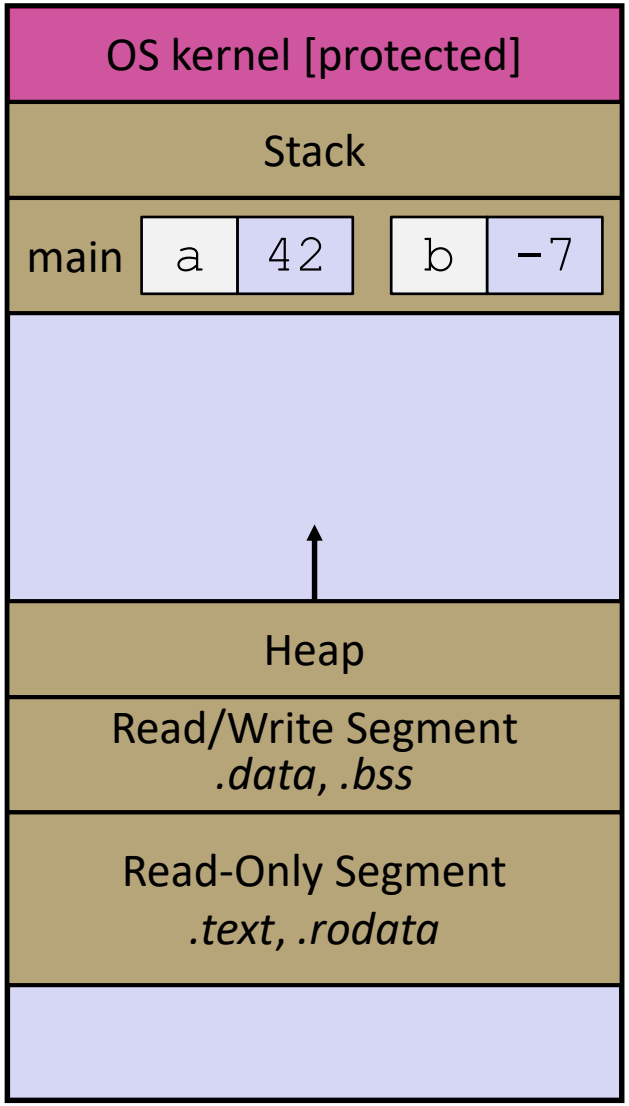


Faking Call-By-Reference in C

- 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

```
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);
  ...
```

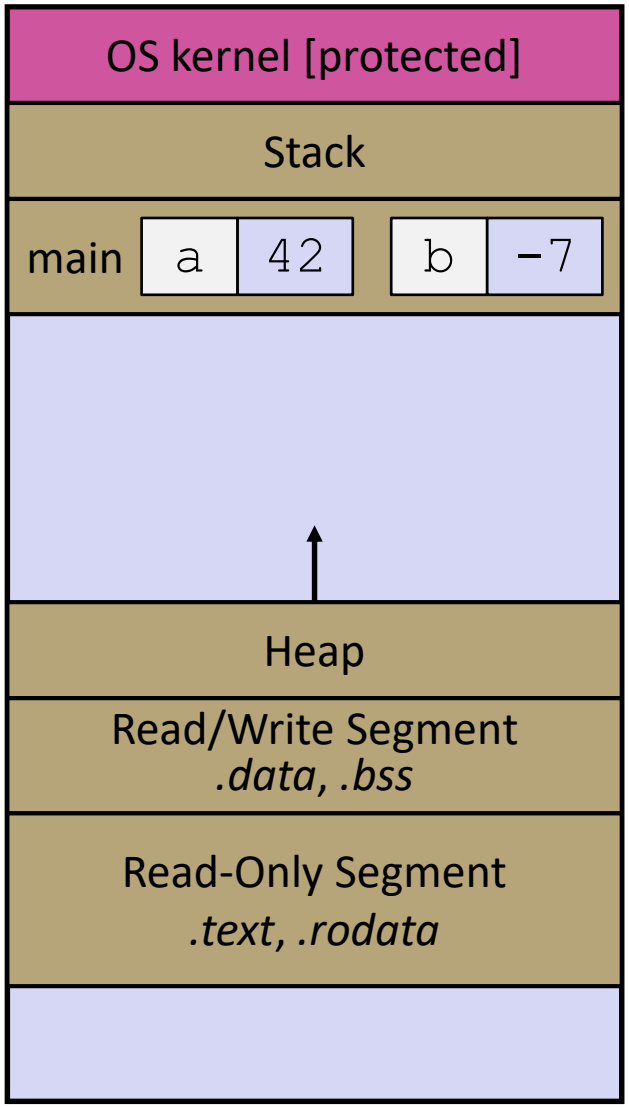
Fixed Swap

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);
  ...
```



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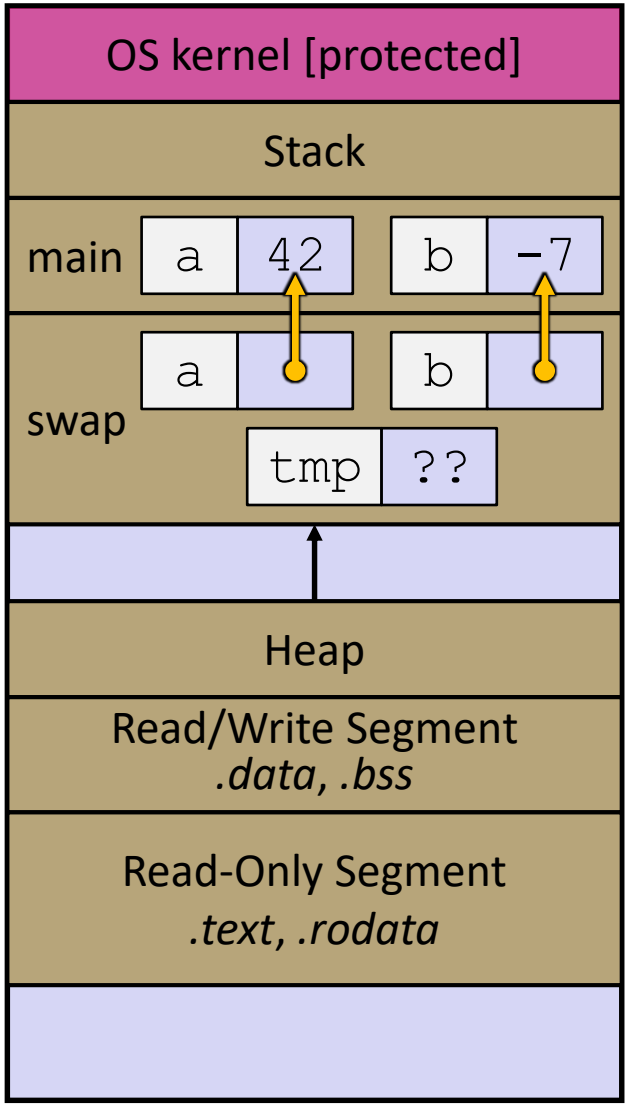

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swap.c

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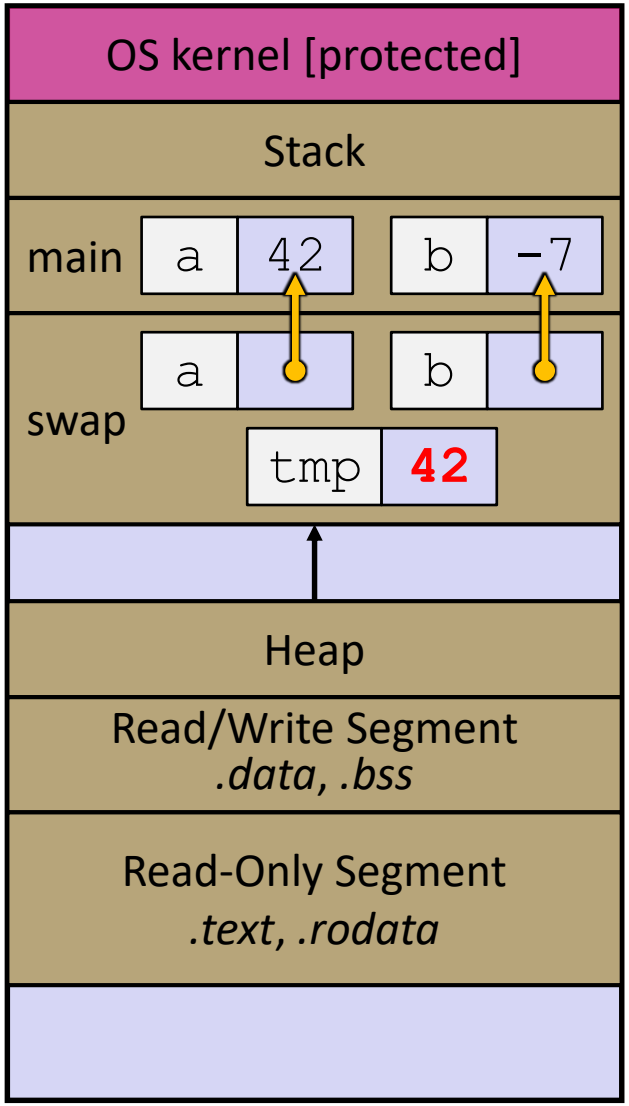

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swap.c

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  int tmp = *a;
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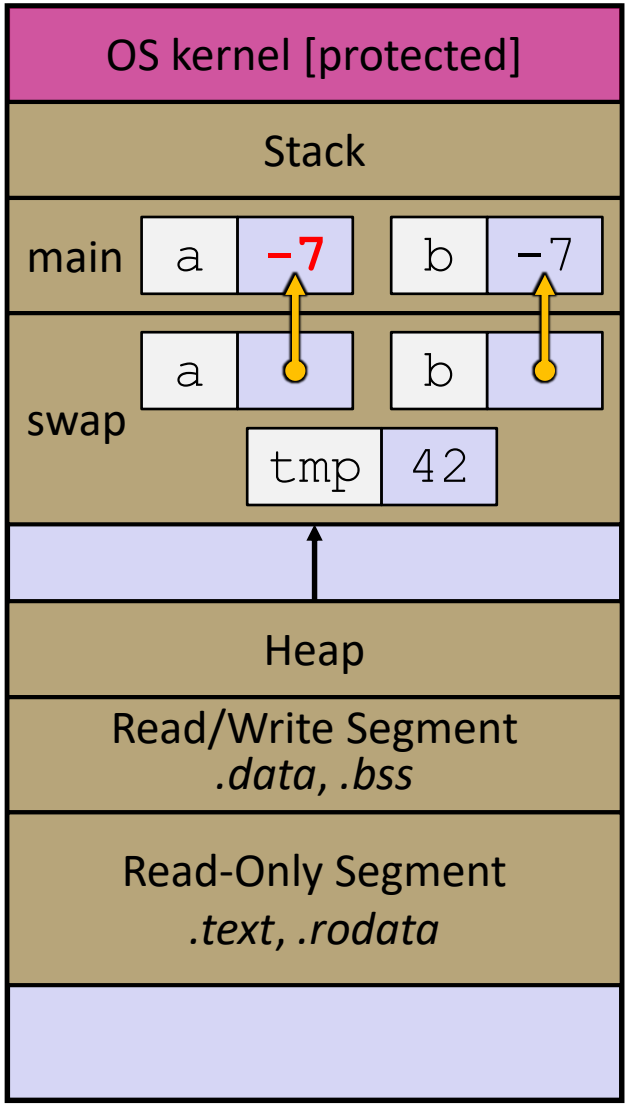

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swap.c

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  int tmp = *a;
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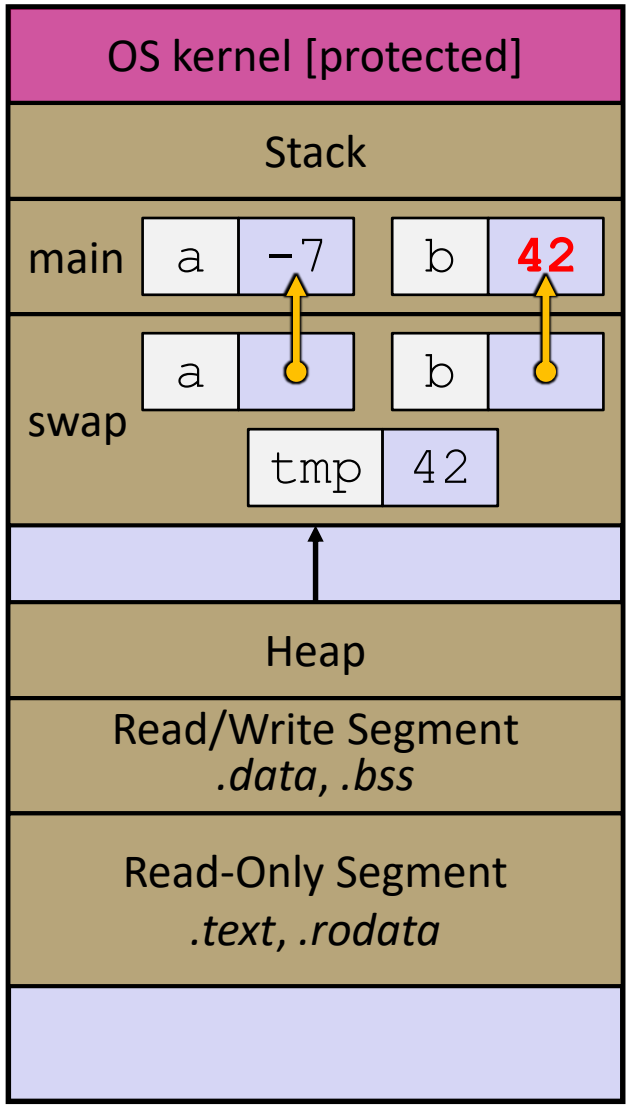

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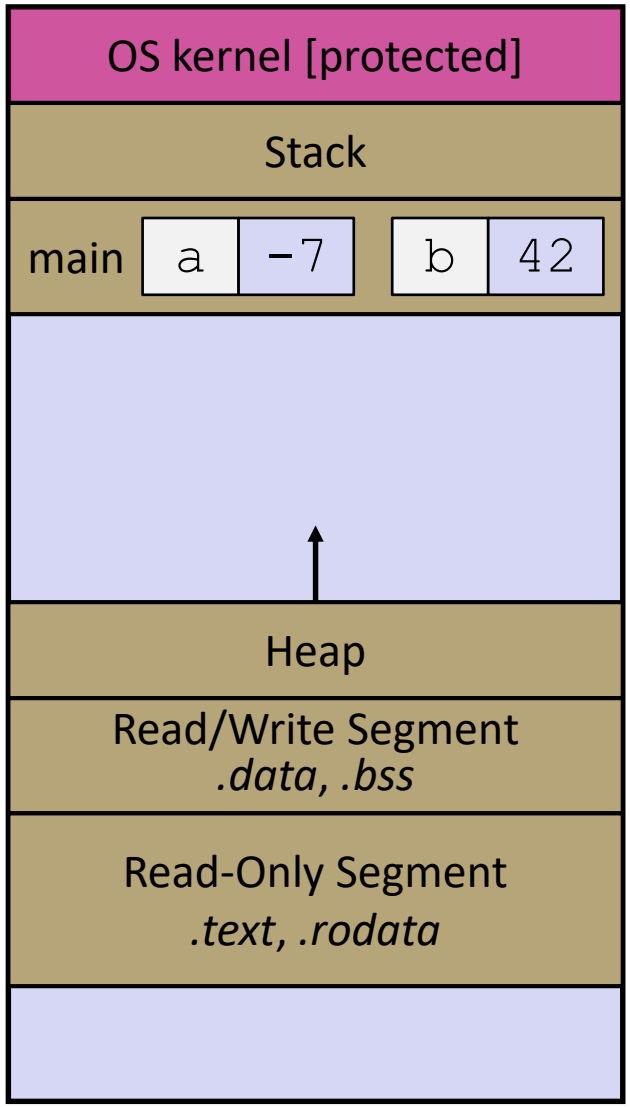


Output Parameters

Warning: Misuse of output parameters is *the* largest cause of errors in HW1!

- Output parameter
  - A pointer parameter used to store (via dereference) a function output value *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 a pointer to that space to Callee (*e.g.*, `&var`)
  3) Callee has an output parameter (*e.g.*, `type* outparam`)
  4) Callee uses parameter to store data in space provided by caller (*e.g.*, `*outparam = value;`)
  5) Caller accesses output via modified data (*e.g.*, `var`)

Lecture Outline

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

Pointers and Arrays

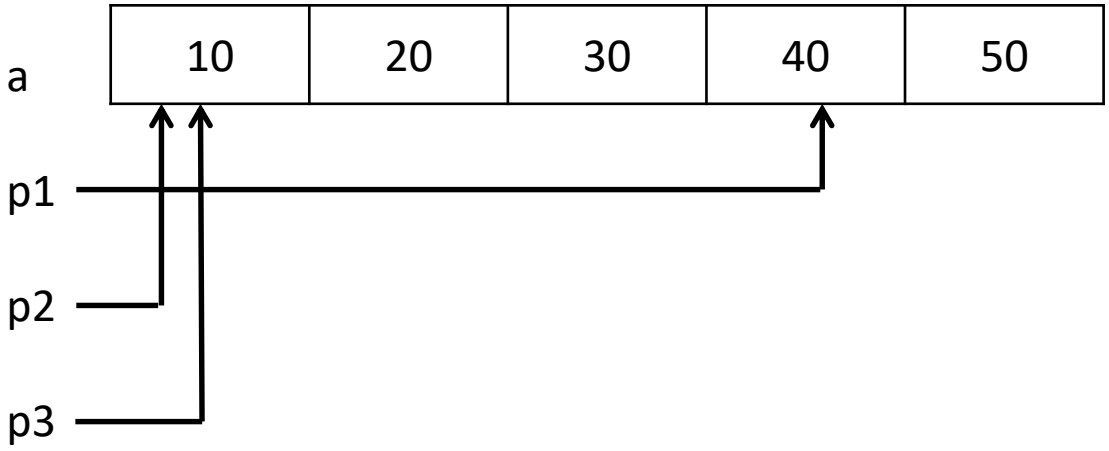
- A pointer can point to an array element
  - You can use array indexing notation on pointers
    - `ptr[i]` is `*(ptr+i)` using pointer arithmetic – reference the data `i` elements forward from `ptr`
  - An array name's value is the beginning address of the array
    - *Like* a pointer to the first 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
```

Pointers and Arrays: Trace

Note: Arrow points to *next* instruction.

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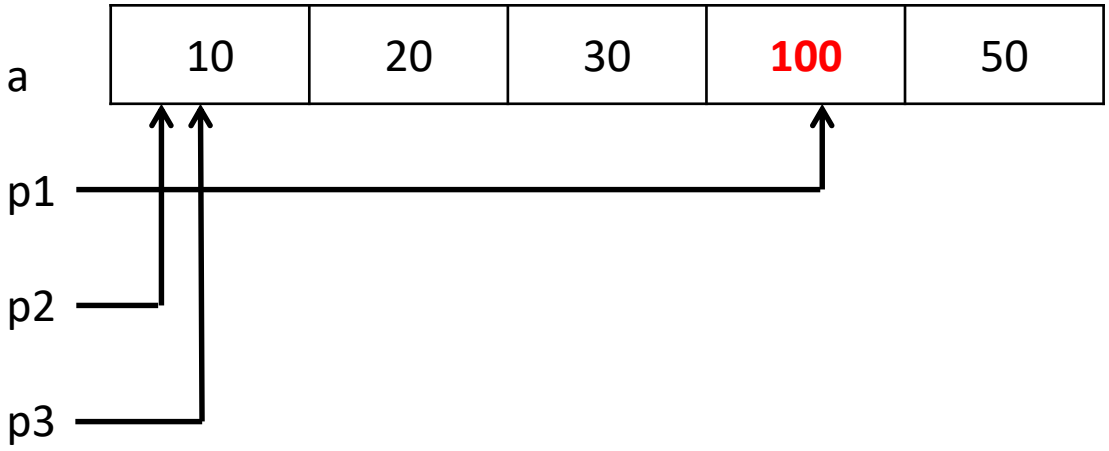


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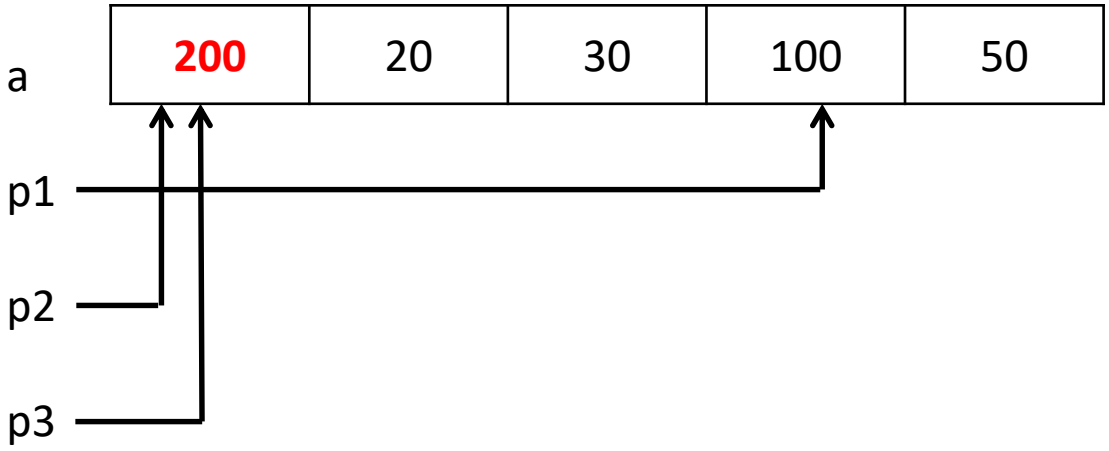


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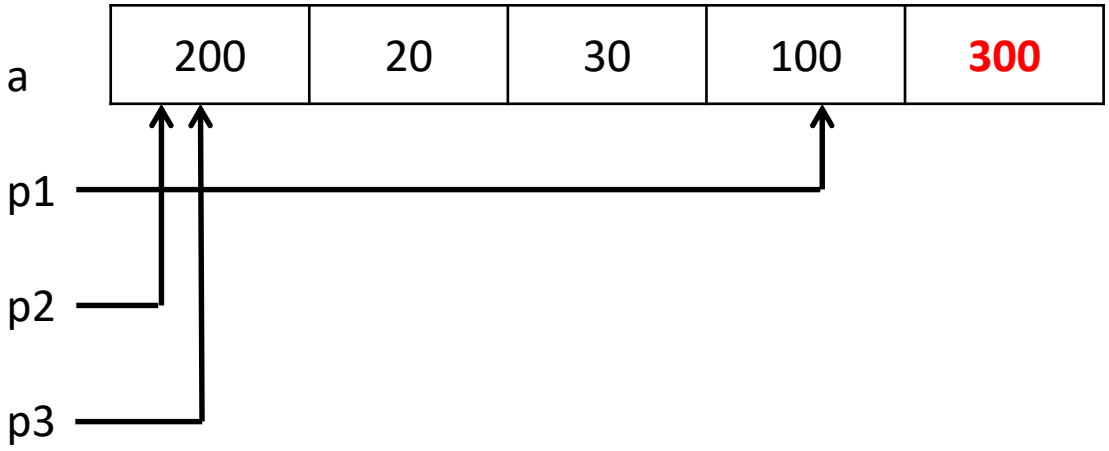


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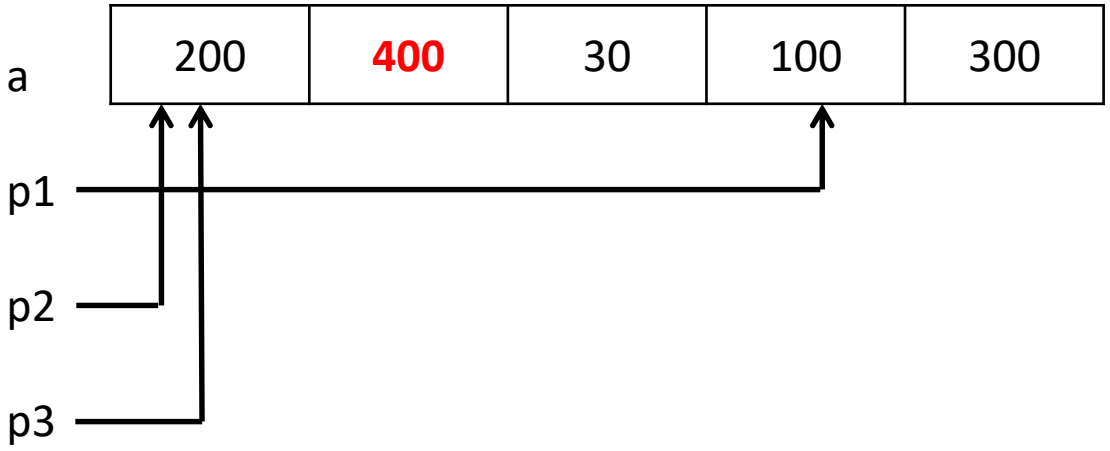


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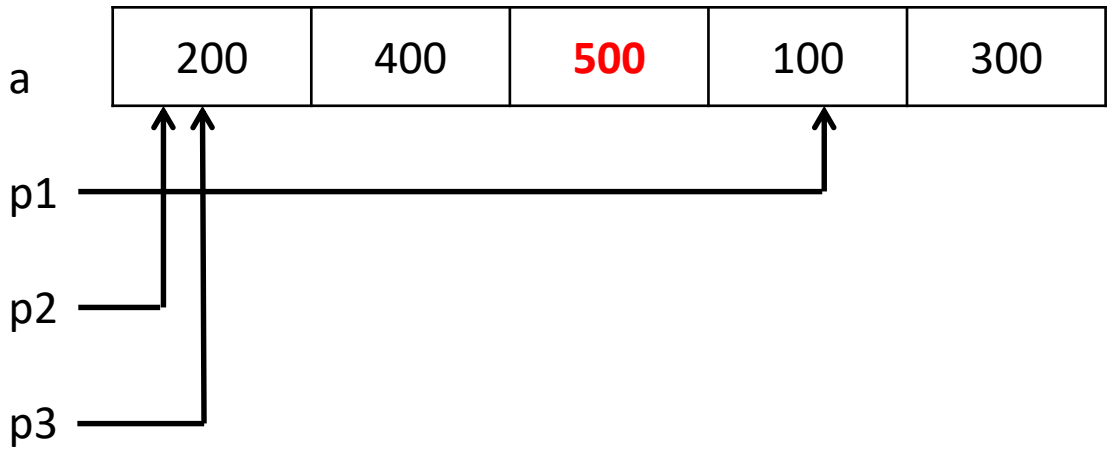


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*p1 = 100;
*p2 = 200;
p1[1] = 300;
p2[1] = 400;
p3[2] = 500;      // final: 200, 400, 500, 100, 300
```

Array Parameters

- Array parameters are *actually* passed (by value) 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[]);

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?

- Using the function:

```
(*name)(arg1, …, argN)
```

  - Calls the pointed-to function with the given arguments and return the return value (but * is optional since all you can do is call it!)

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

map.c

Function Pointer Example

- C allows you to omit & on a function parameter and omit * when calling pointed-to function; both assumed implicitly.

```
#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 EXIT_SUCCESS;
}
```

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