Poll Everywhere

pollev.com/naomila

About how long did Exercise 1 take you?

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

CSE333 Systems Programming

Pointers

Instructors:

Naomi Alterman

Teaching Assistants:

Ann Baturytski	Barbora Buzkova	Mendel Carroll
Camden Harris	Hannah Hempstead	Rishabh Jain
Irene Lau	Jonathan Nister	Advay Patil
Aviel Wood	Angela Wu	Jennifer Xu

Administrivia (1/3)

- Exercise grading
  - Sample solutions released same day as deadline
  - Autograder scores should be visible around Sunday
  - Full grades follow shortly after
  - 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

Administrivia (2/3)

- Pre-quarter survey (Google form) due tonight
- Exercise 2 out today and due Friday (4/10) morning
- Homework 1 out tonight, due in 2 weeks (Thu 4/16)
  - Linked list and hash table implementations in C
  - Get starter code by cloning your new *homework* repo

Administrivia (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

Lecture Outline

- **Arrays**
- Pointer Basics
- Parameters
- Pointer Arithmetic

Arrays (review from last lec)

int nums[5]

32 bit machine

5 * 4 = 20 bytes

- Definition: `type name[size]` allocates `size*sizeof(type)` bytes of *contiguous* memory
  - By default, array values are "mystery" data (*i.e.*, uninitialized)
  - Normal usage is a compile-time constant for `size`
    e.g., `int scores[175];`

- Size of an array
  - Not stored anywhere – array does not know its own size!
    - `sizeof(array)` only works in the variable scope of array definition

Using Arrays

- Initialization: `type name[size] = {val0,…,valN};`
  - `{}` initialization can *only* be used at time of definition
  - If no size supplied, infers from length of array initializer

- Array name used as identifier for "collection of data"
  - **Array name, in code, produces the address of the start of the array**
    - Cannot be assigned to / changed
  - `name[index]` specifies an element of the array and can be used as an assignment target or as a value in an expression
    - **Is actually `*(name+index)`** with pointer arithmetic

```
int primes[6] = {2, 3, 5, 6, 11, 13};
primes[3] = 7;
primes[100] = 0;  // memory smash!
```

Multi-dimensional Arrays

- Generic 2D format:
  `type name[rows][cols] = {{values},…,{values}};`
  - Still allocates a single, contiguous chunk of memory
  - C is *row-major*

```
// a 2-row, 3-column array of doubles
double grid[2][3];

// a 3-row, 5-column array of ints
int matrix[3][5] = {
  {0, 1, 2, 3, 4},
  {0, 2, 4, 6, 8},
   {1, 3, 5, 7, 9}
};
```

in mem:
0, 1, 2, 3, 4, 0, 2, 4, 6, 8, 1, 3, 5, 7, 9

  - 2-D arrays normally only useful if size known in advance; otherwise, use dynamically-allocated data

matrix math (gfx, ML, useless number fun)

Structs

- The *size* and *layout* of a struct instance is completely determined by (1) the field ordering and (2) alignment requirements
  - Can review 351 if curious
- Compiler figures these things out at compile-time and will replace these "function calls" with their results before machine code generation
  - `sizeof(type)` returns the size in bytes
  - `offsetof(type, field)` returns offset value in bytes
    - Defined in `stddef.h`
- We'll talk more about struct usage in Lecture 4

Lecture Outline

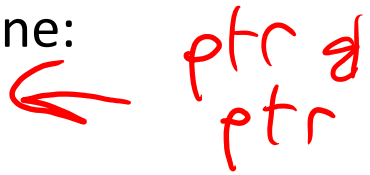
- Arrays
- **Pointer Basics**
- Parameters
- Pointer Arithmetic

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

Pointers

- Variable that store
  - points to some
  - &foo produces the
- Generic definition: name; or type *n
  - Recommended: d multiple pointers on same
    int *p1, p2; as int *p1, *p2;
  - Instead, use:
- *Dereference* a
  - Access the m

Bjarne don't care

The choice between `int* p;` and `int *p;` is not about right and wrong, but about style and emphasis. C emphasized expressions; declarations were often considered little more than a necessary evil

https://www.stroustrup.com/bs_faq2.html#whitespace

a number that happens to be an address to an int in memory

Box-and-Arrow Diagrams (1/4)

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

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;
}
```

fn's local variables

address	name	value

address var name value

&x	x	value
&arr[2]	arr[2]	value
&arr[1]	arr[1]	value
&arr[0]	arr[0]	value
&p	p	value

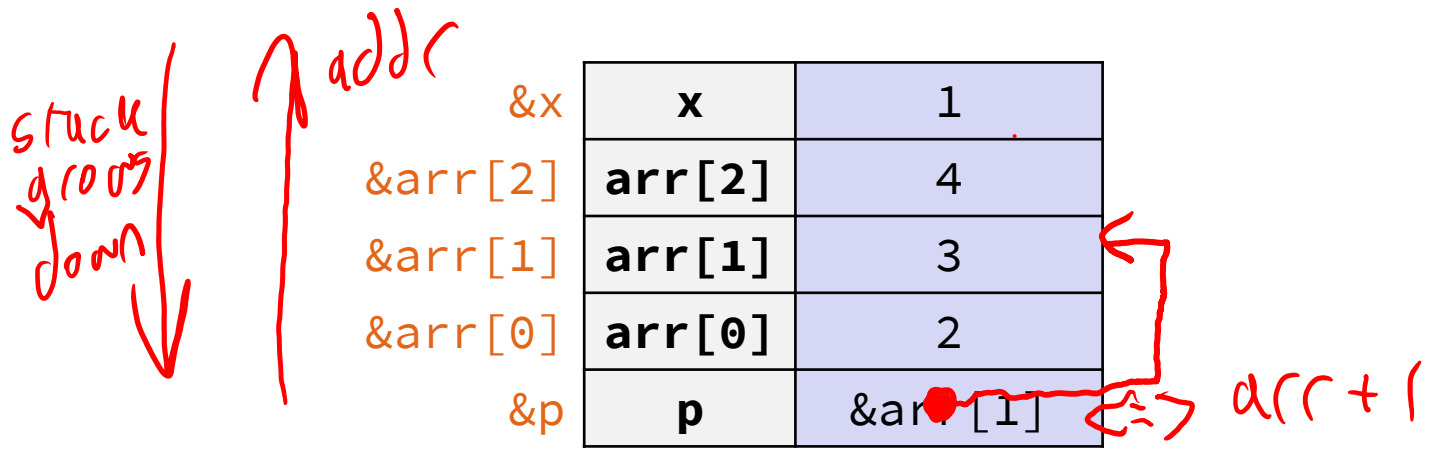
stack frame for main()

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

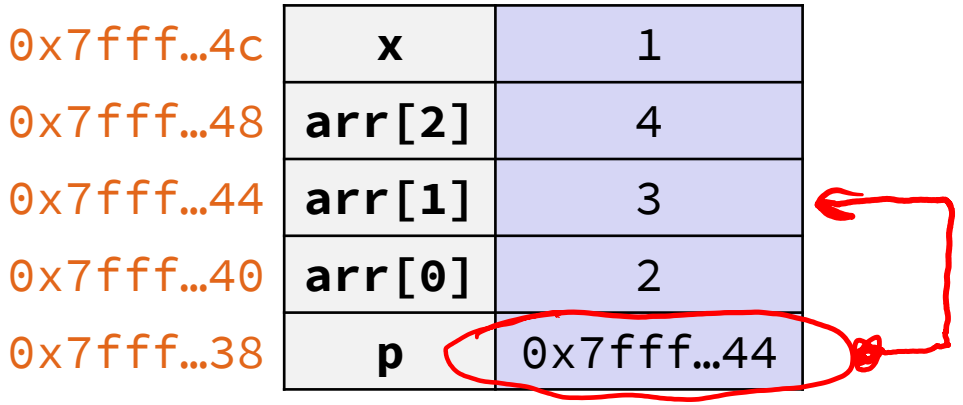


Box-and-Arrow Diagrams (4/4)

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



Lecture Outline

- Arrays
- Pointer Basics
- **Parameters**
- Pointer Arithmetic

Parameters: Reference vs. Value

- There are two fundamental parameter-passing schemes in programming languages
- Pass-by-value / "call-by-value"
  - Parameter is a local variable initialized with a copy of the calling argument when the function is called; manipulating the parameter only changes the copy, *not* the calling argument
  - **C**, **Java**, C++ (most things)
- Pass-by-reference / "call-by-ref"
  - Parameter is an alias for the supplied argument; manipulating the parameter manipulates the calling argument
  - C++ references (we'll see these later)

Arrays as Parameters

- It's tricky to use arrays as parameters
  - What happens when you use an array name as an argument?
  - Arrays do not know their own size

```
int SumAll(int a[]);  // prototype

int main(int argc, char** argv) {
  int numbers[] = {9, 8, 1, 9, 5};
  int sum = SumAll(numbers);
  return 0;
}

int SumAll(int a[]) {
  int i, sum = 0;
  for (i = 0; i < ...???
}
```

Standard Idiom: Pass Size as Parameter

```
int SumAll(int a[], int size);  // prototype

int main(int argc, char** argv) {
  int numbers[] = {9, 8, 1, 9, 5};
  int sum = SumAll(numbers, 5);
  printf("sum is: %d\n", sum);
  return 0;
}

int SumAll(int a[], int size) {
  int i, sum = 0;
  for (i = 0; i < size; i++) {
    sum += a[i];
  }
  return sum;
}
```

arraysum.c

Arrays: Call-by-what?

- Technical answer: a `T[]` array parameter is "promoted" to a pointer of type `T*`, and the *pointer* is passed by value
  - So it acts like a *call-by-reference array* – caller's array can be changed if callee modifies the array parameter elements
  - But it's really a *call-by-value pointer* – the callee's pointer parameter can be changed without affecting the caller's array
    - This is because `T[i]` is really `*(T+i)`. We aren't changing T!

```
void CopyArray(int src[], int dst[], int size) {
  int i;
  dst = src;  // doesn't copy the array, copies the address
  for (i = 0; i < size; i++) {
    dst[i] = src[i];  // copies source array to itself
  }
}
```

Array Parameters

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

This code:

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

int main( ... ) {
  int a[5];
  ...
  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) {
```

Returning an Array

- Local variables, including arrays, are allocated on the Stack
  - They "disappear" when a function returns!
  - Can't safely return local arrays from functions
    - Can't return an array as a return value – why not?

```
int* CopyArray(int src[], int size) {
  int i, dst[size];   // OK in C99

  for (i = 0; i < size; i++) {
    dst[i] = src[i];
  }

  return dst;  // no compiler error, but wrong!
}
```

buggy_copyarray.c

Solution: Output Parameter

- Create the "returned" array in the caller
  - Pass it as an output parameter to `CopyArray()`
    - A pointer parameter that allows the called function to store values that the caller can use
  - Works because arrays are "passed" as pointers

```
void CopyArray(int src[], int dst[], int size) {
  int i;

  for (i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```

copyarray.c

foo (int *src, int *dst, int src_size, int * dst_size)

int src[5] = ...
int dst[99];
int dst_size;
Foo (src, dst, 5, &dst_size);

Array Memory Diagram (1/3)

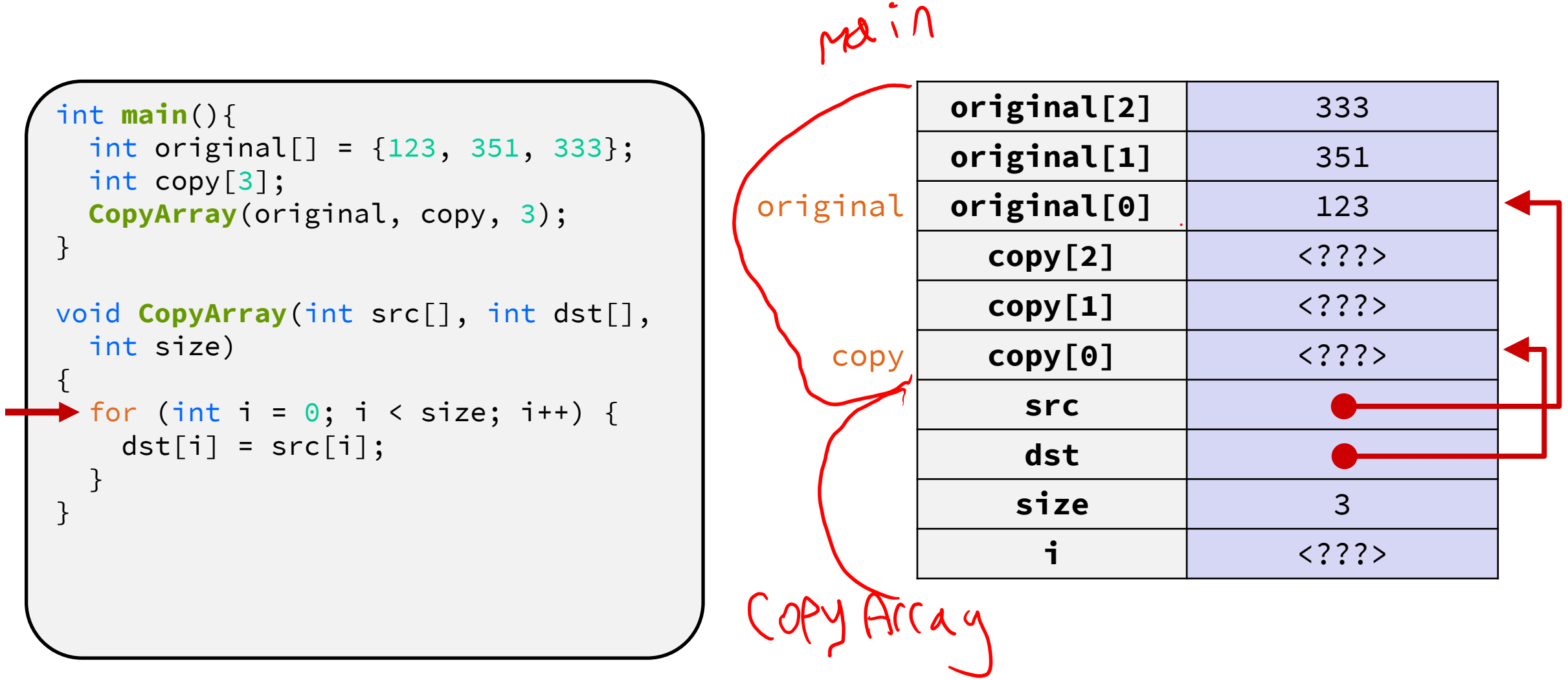
```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

void CopyArray(int src[], int dst[],
  int size)
{
  for (int i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```

Stack Frame for main

	original[2]	333
	original[1]	351
original	original[0]	123
	copy[2]	<???>
	copy[1]	<???>
copy	copy[0]	<???>

Array Memory Diagram (2/3)

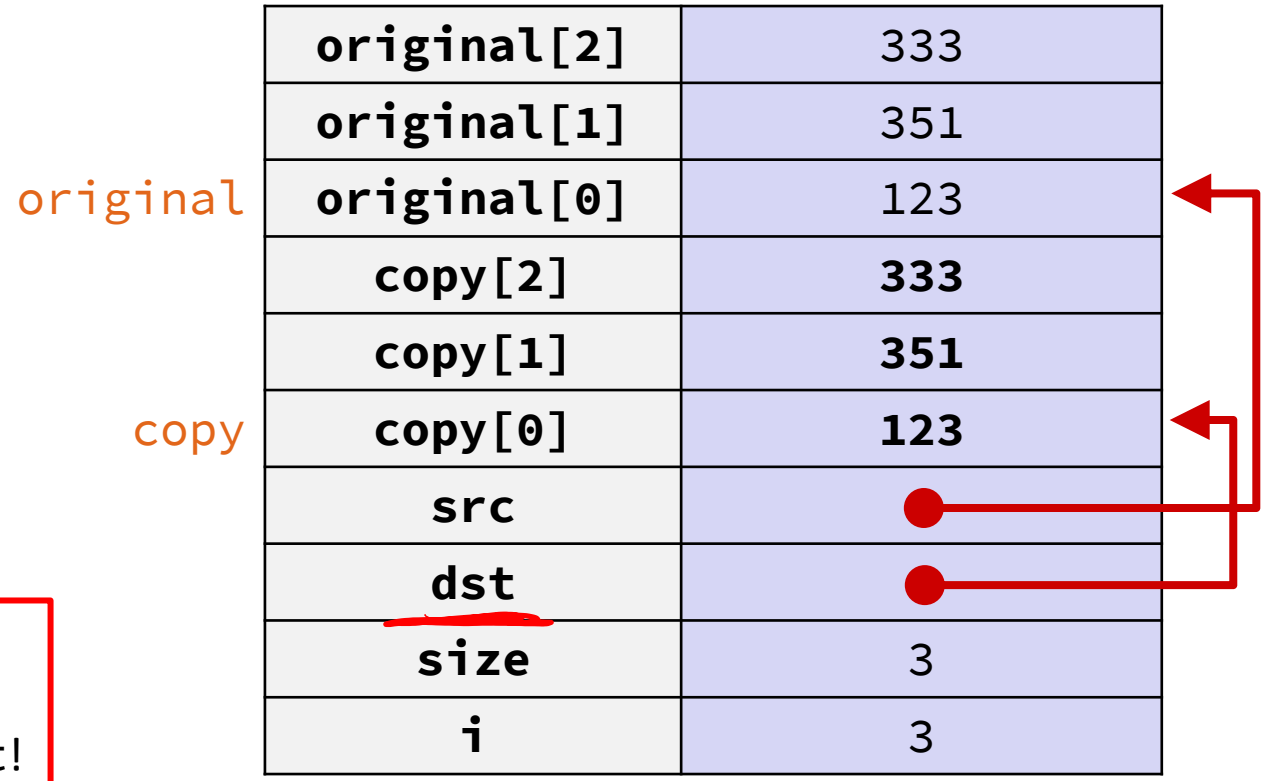
```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

void CopyArray(int src[], int dst[],
  int size)
{
  for (int i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```



Array Memory Diagram (3/3)

```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

void CopyArray(int src[], int dst[],
  int size)
{
  for (int i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```

dst[i] is really *(dst+i). We aren't changing dst!



Array Memory Diagram (4/4)

```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

void CopyArray(int src[], int dst[],
  int size)
{
  for (int i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```

	original[2]	333
	original[1]	351
original	original[0]	123
	copy[2]	333
	copy[1]	351
copy	copy[0]	123

Output Parameters

- Output parameters are common in library functions
  - `long int strtol(char* str, char** endptr, int base);`
  - `int sscanf(char* str, char* format, ...);`

```
int   num, i;
char* p_end, str1 = "333 rocks";
char  str2[10];

// converts "333 rocks" into long - p_end is conversion end
num = (int) strtol(str1, &p_end, 10);

// reads string into arguments based on format string
num = sscanf("3 blind mice", "%d %s", &i, str2);
```

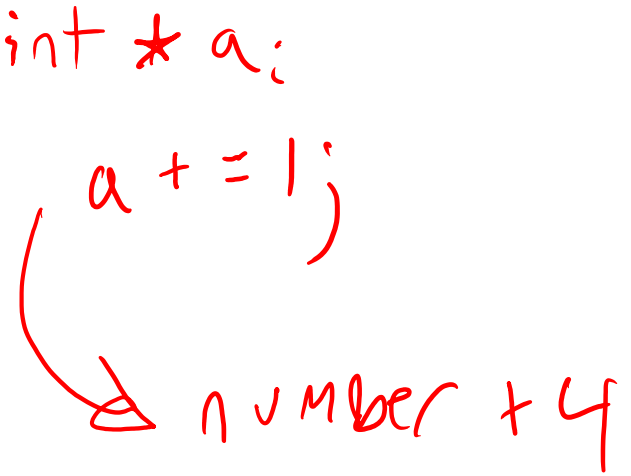
outparam.c

Lecture Outline

- Arrays
- Pointer Basics
- Parameters
- **Pointer Arithmetic**

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

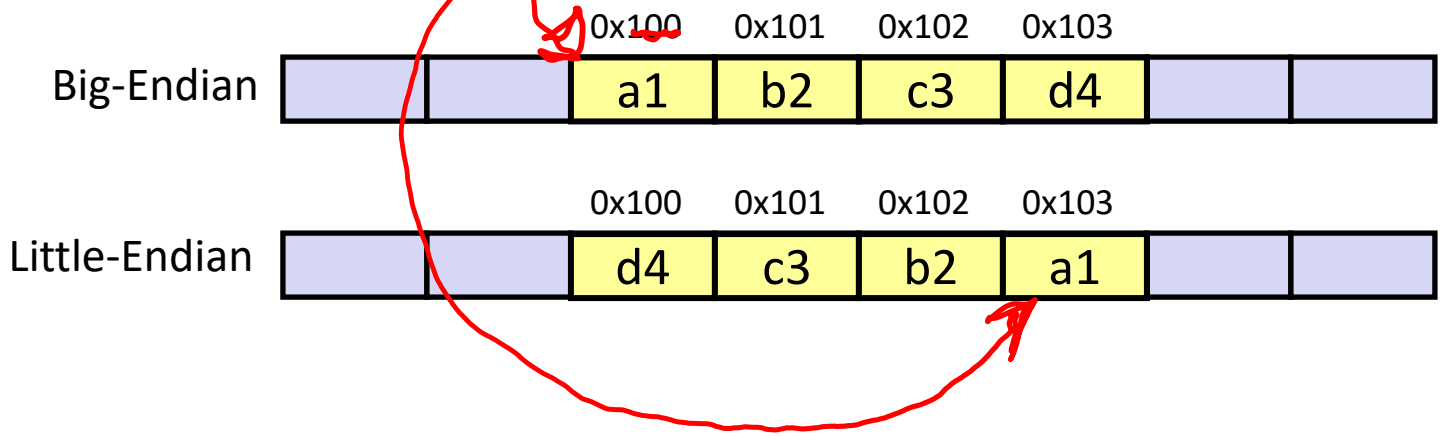
- A pointer can point to an array element
  - You can use array indexing notation on pointers
    - `ptr[i]` is `*(ptr+i)` with pointer arithmetic – reference the data `i` elements forward from `ptr`
  - An array name's value is the beginning address of the array
    - *Like* a pointer to the first element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

```
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
```

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

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

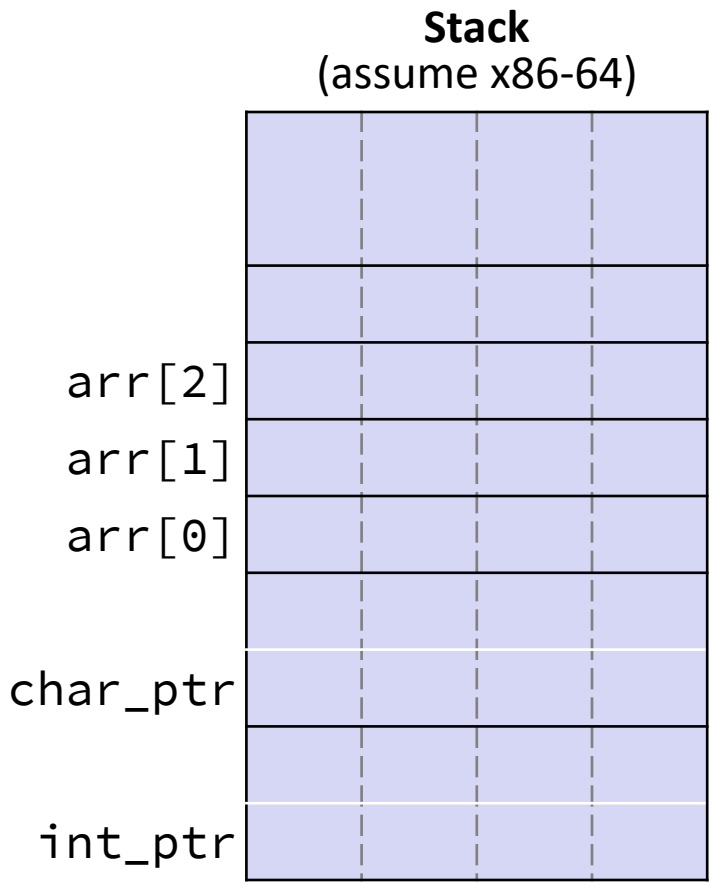


Pointer Arithmetic Example (1/10)

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;
}
```

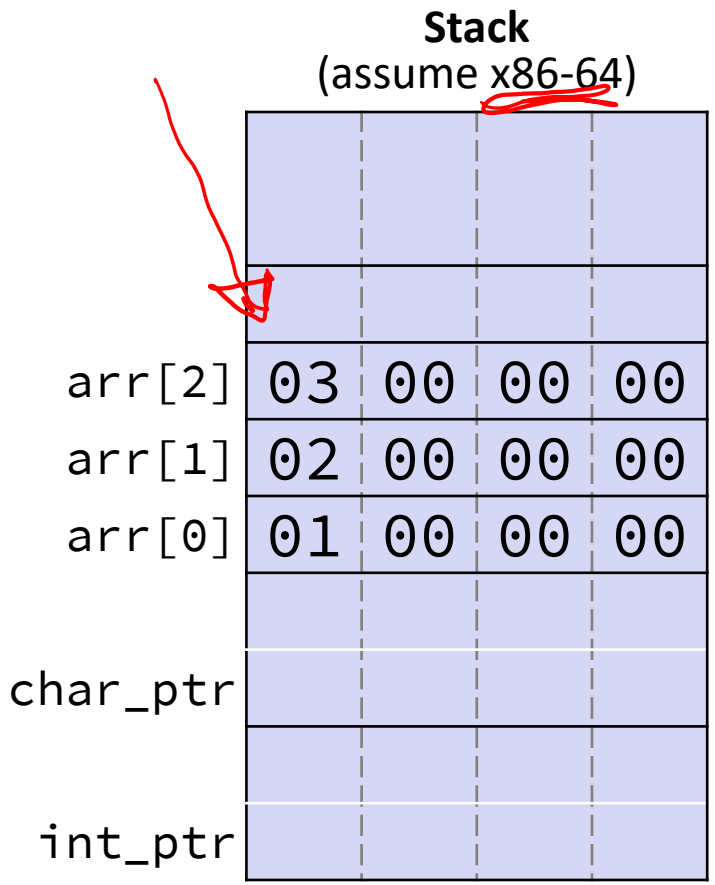
pointerarithmetic.c



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;
}
```

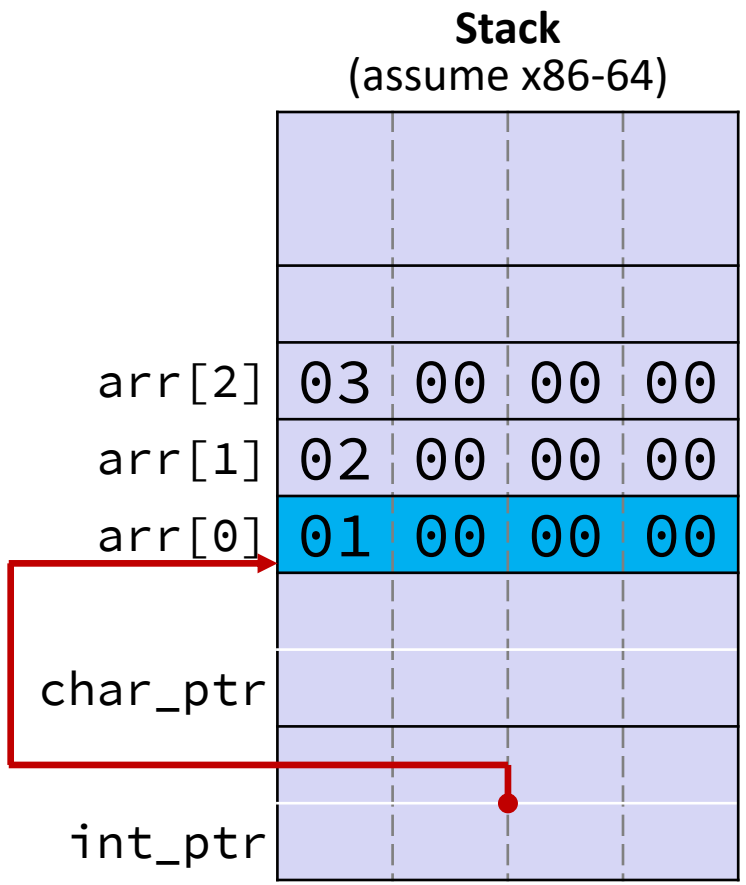
pointerarithmetic.c



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;
}
```

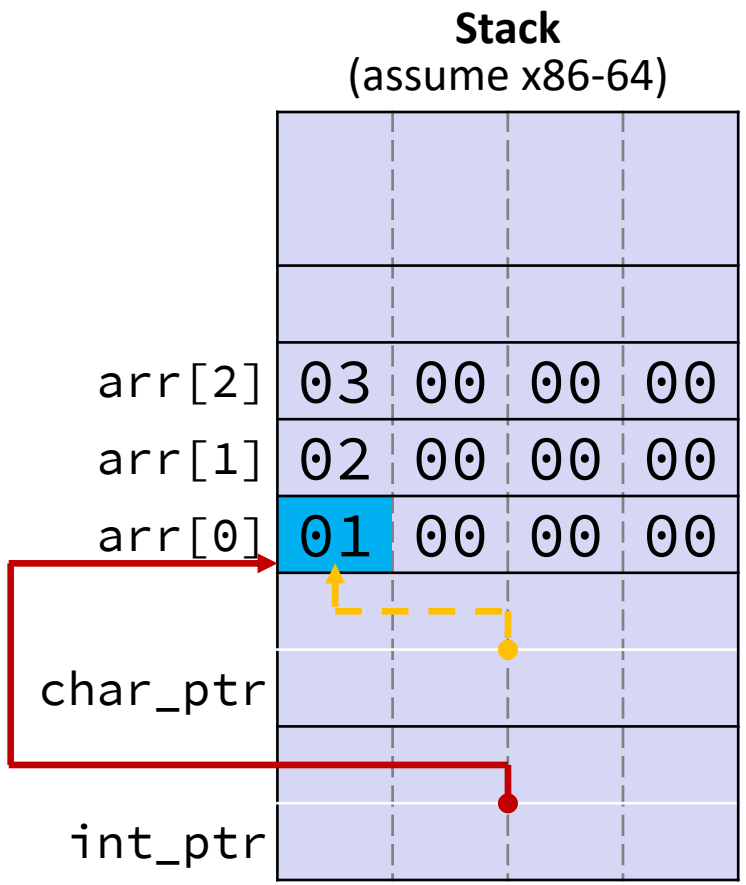
pointerarithmetic.c



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

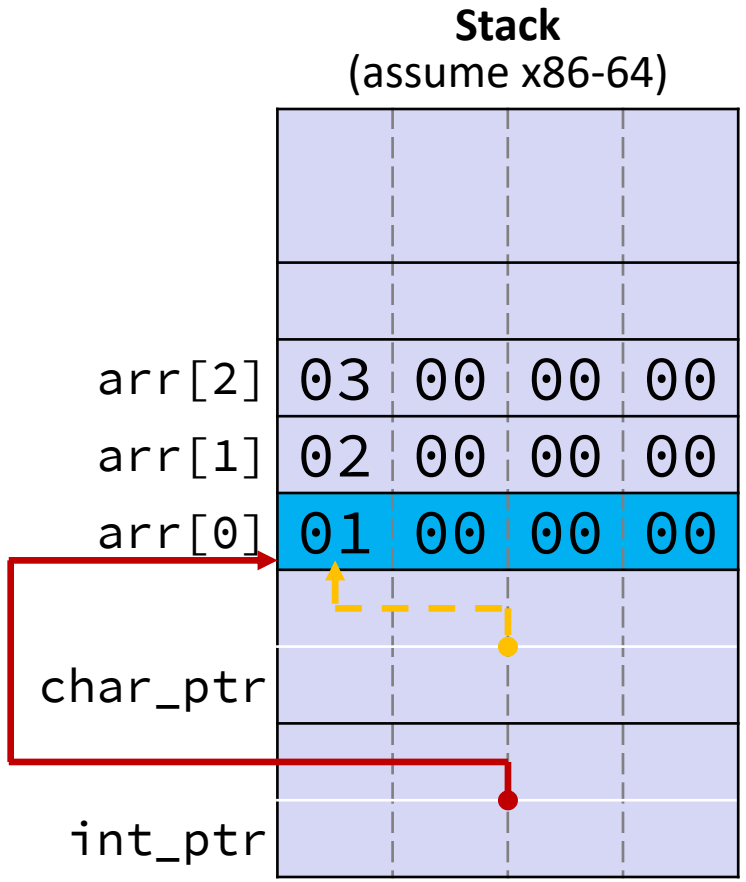


Pointer Arithmetic Example (5/10)

```
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

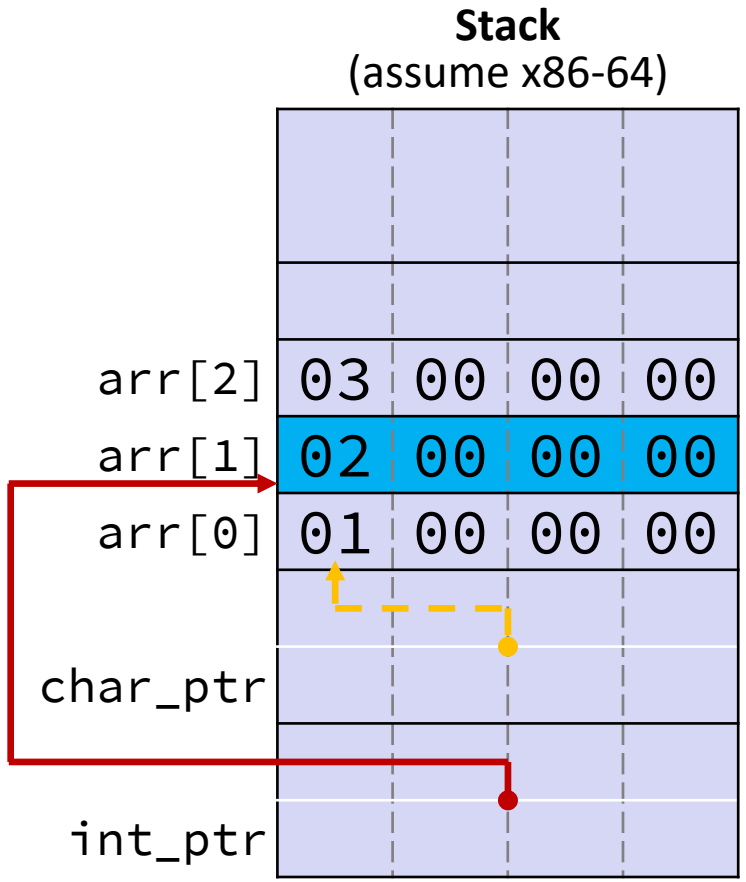


Pointer Arithmetic Example (6/10)

```
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

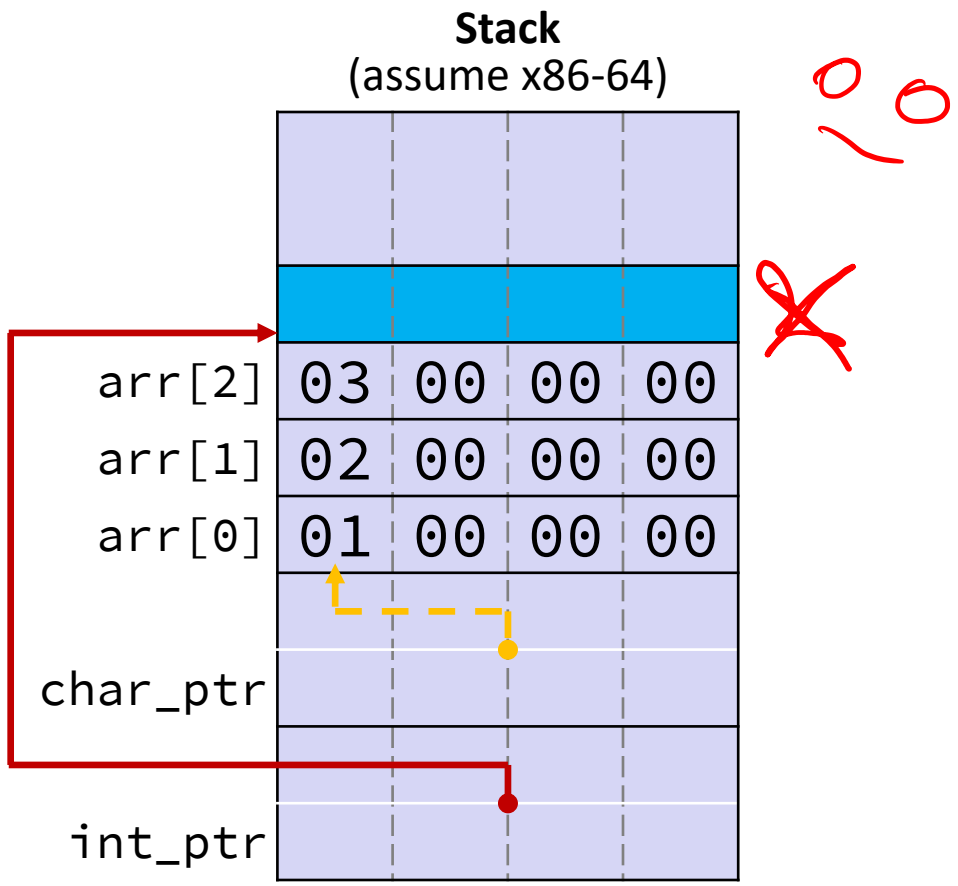


Pointer Arithmetic Example (7/10)

```
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:** ???

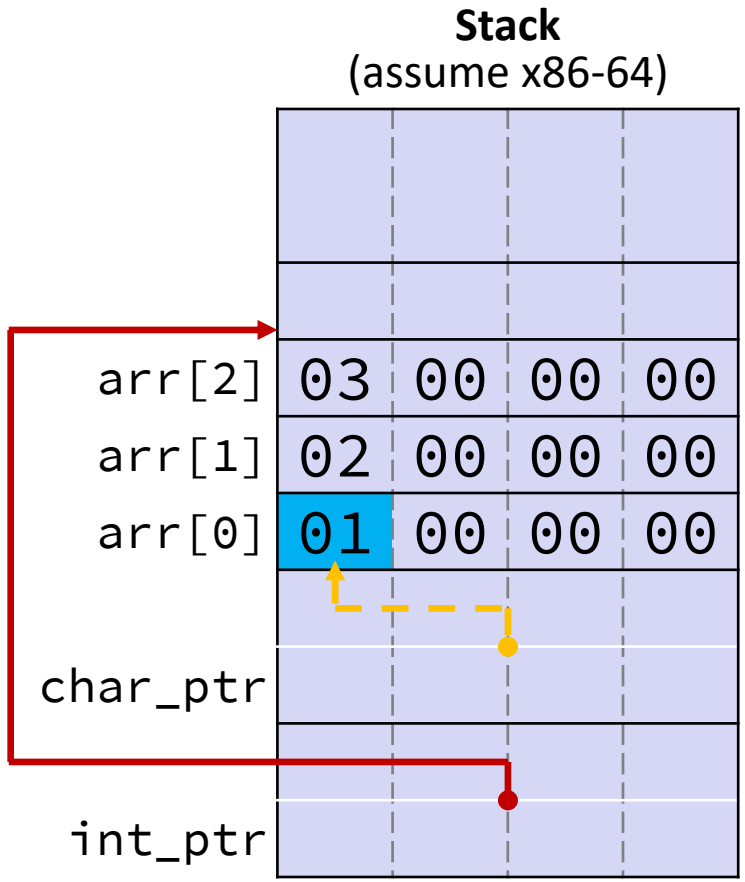


Pointer Arithmetic Example (8/10)

```
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

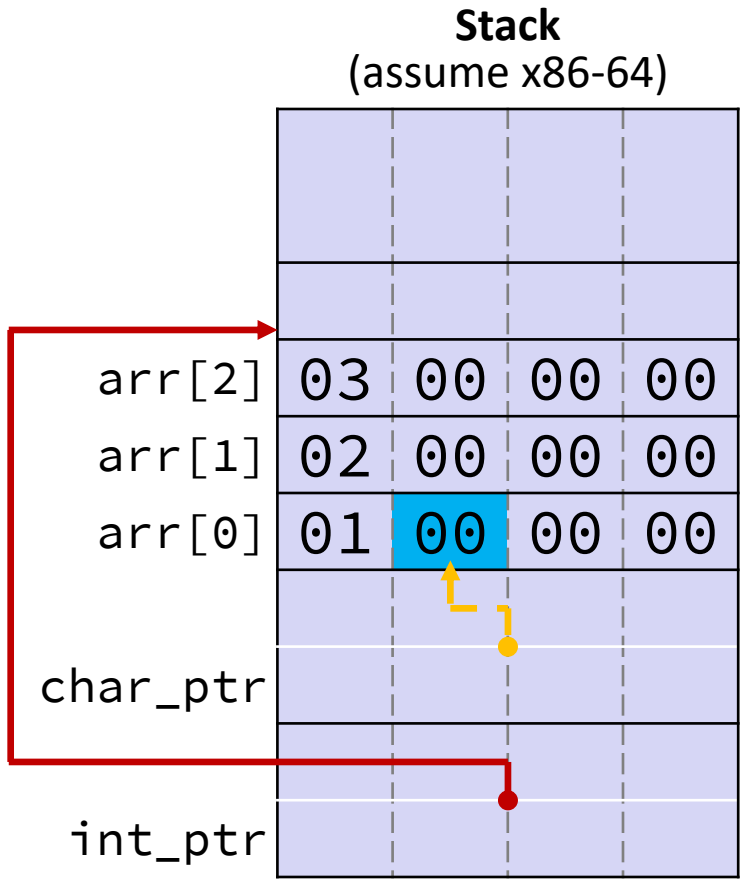


Pointer Arithmetic Example (9/10)

```
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

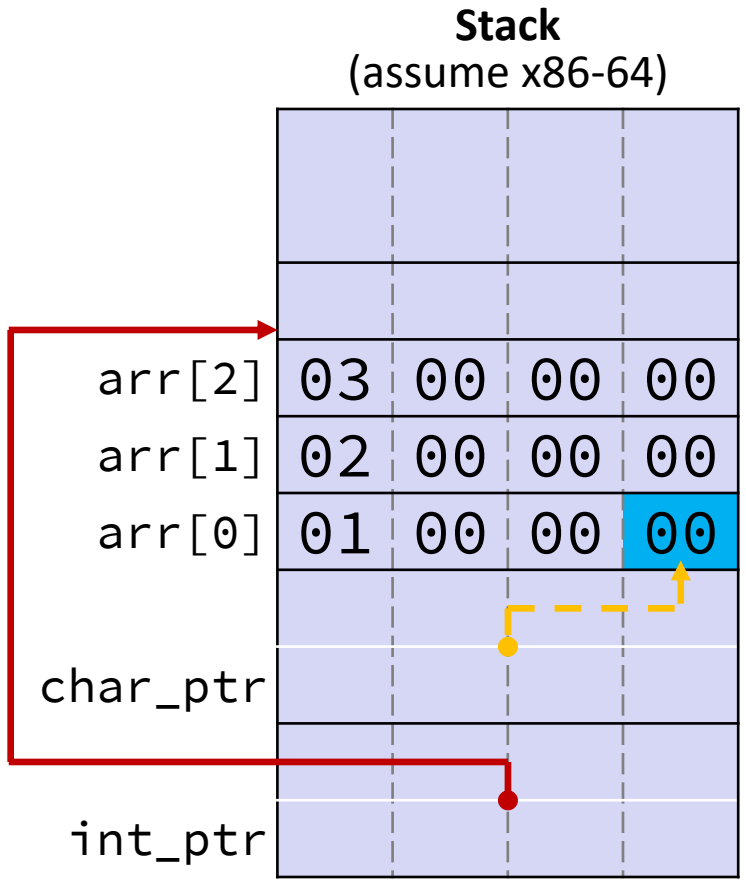


Pointer Arithmetic Example (10/10)

```
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



Extra Exercise #1

- Write a function that:
  - Accepts an array of 32-bit unsigned integers and a length
  - Reverses the elements of the array in place
  - Returns nothing (`void`)

Extra Exercise #2

- 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 #3

- 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