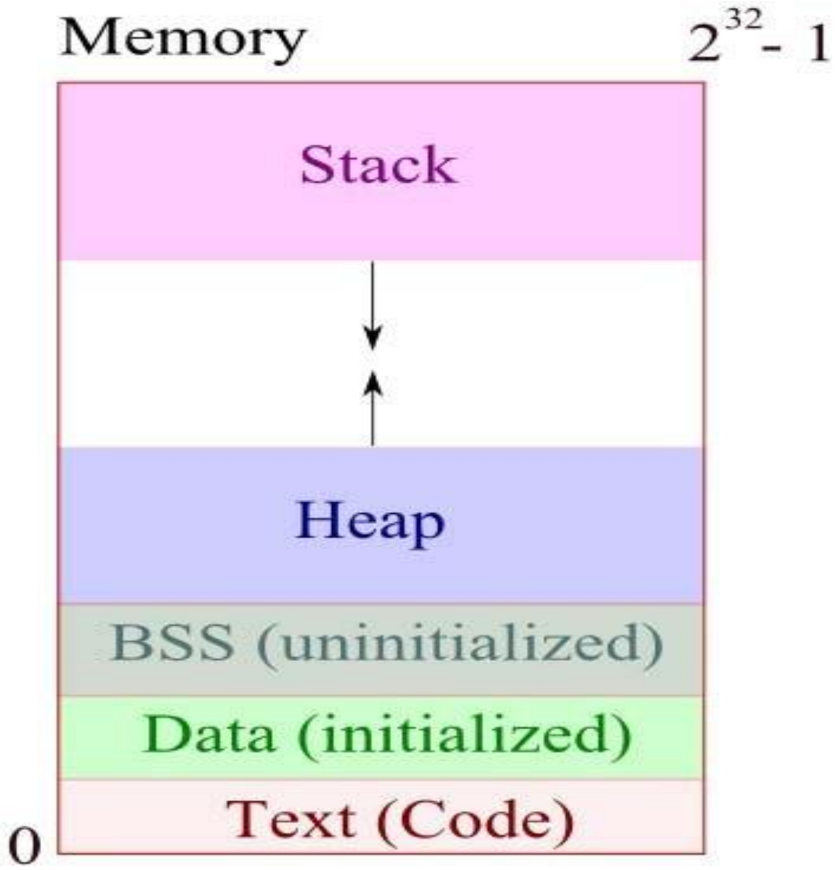
Memory Management

Mohamed Saied

Agenda

- Memory layout
- Stack memory in details
- Raw pointers
- References
- Ptr vs ref

Memory Layout



Memory Layout diagram courtesy of bogotobogo.com

Outline

- The Course consists of the following topics:
  - Memory Layout
  - **Stack**
  - Call Stack
  - Data Segment
  - Heap
  - Rodata segment

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Stack

- Stack contains local variables from functions and related book-keeping data. LIFO structure.
  - Function variables are pushed onto stack when called.
  - Functions variables are popped off stack when return.

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Call Stack

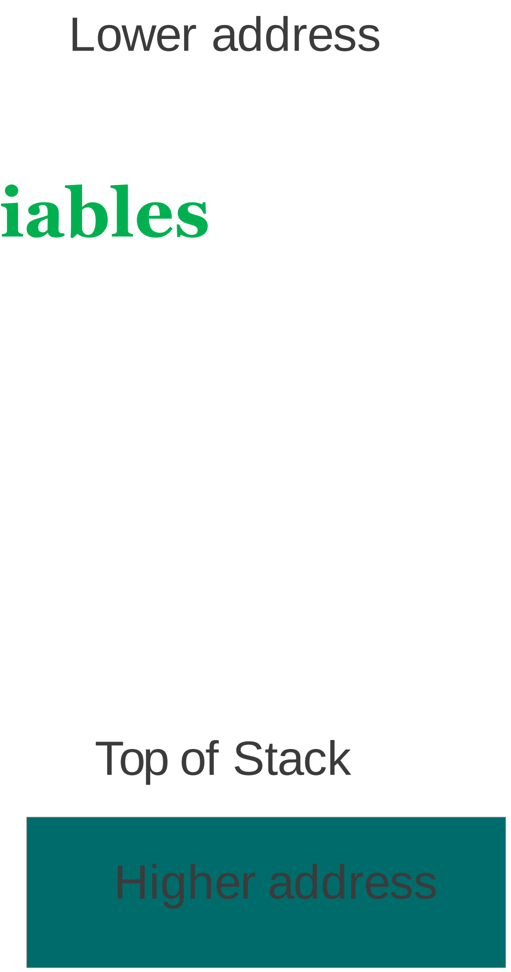
Example: DrawSquare called from main()

```
void DrawSquare(int i){
    int start, end, …. //other local variables
    DrawLine(start, end);
 }
 void DrawLine(int start, int end){
    //local variables
    ...
 }
```

Call Stack

Example:

```
void DrawSquare(int i){
    int start, end, .... //other local variables
    DrawLine(start, end);
 }
 void DrawLine(int start, int end){
    //local variables
    ...
 }
```



Lower address

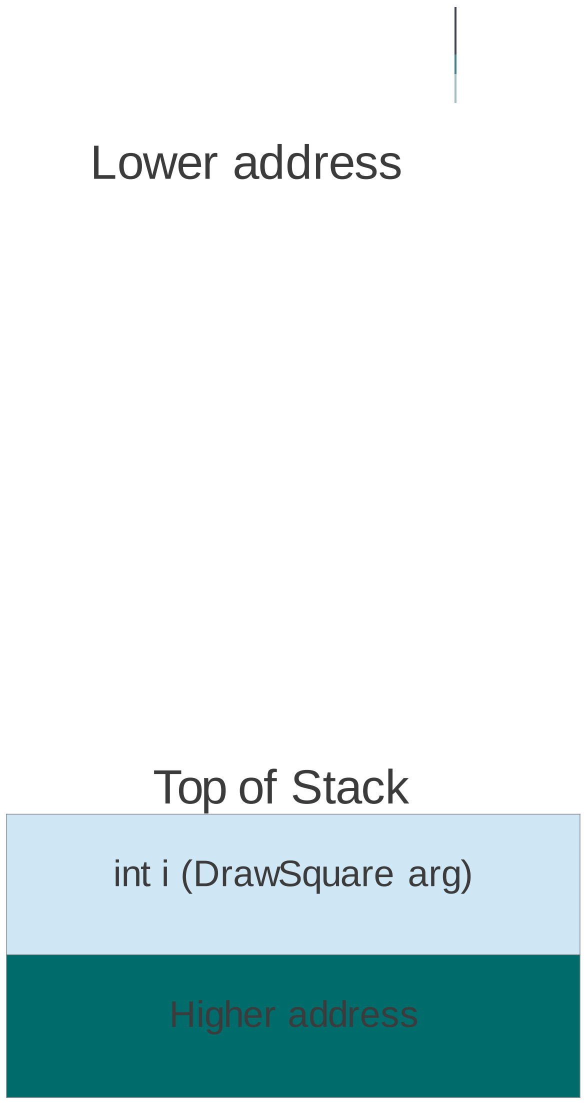
Top of Stack

Higher address

Call Stack

Example: DrawSquare is called in main

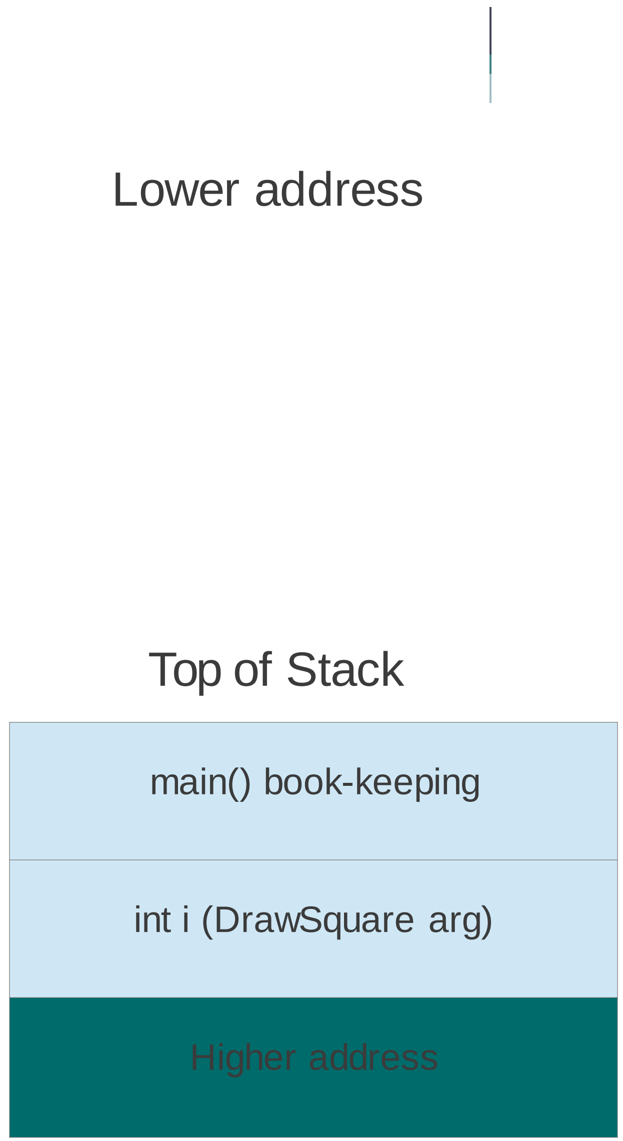
```
void DrawSquare(int i){
    int start, end, ...
    DrawLine(start, end);
}
void DrawLine(int start,  int end){
    //local variables
    ...
    }
```



Call Stack

Example:

```
void DrawSquare(int i){
    int start, end, ...
    DrawLine(start, end);
}
void DrawLine(int start,  int end){
    //local variables
        ...
    }
```



Lower address

Top of Stack

main() book-keeping

int i (DrawSquare arg)

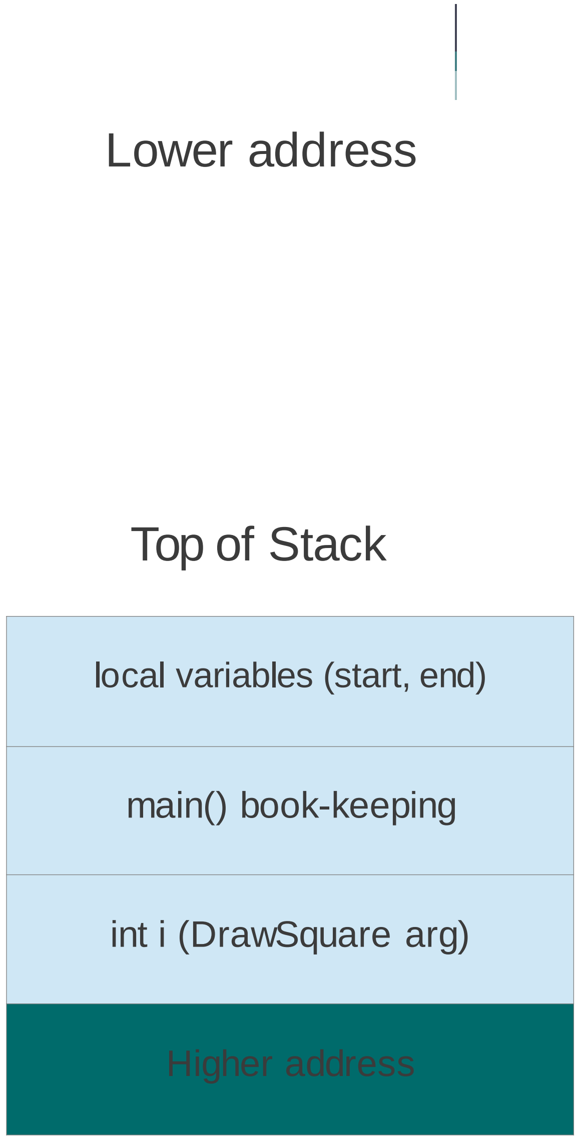
Higher address

Call Stack

Example:

```
  void DrawSquare(int i){

    int start, end, ...

    DrawLine(start, end);
}
void DrawLine(int start,  int end)
{       //local variables
        ...

 }
```

DrawSquare
Stack Frame



Lower address

Top of Stack

local variables (start, end)

main() book-keeping

int i (DrawSquare arg)

Higher address

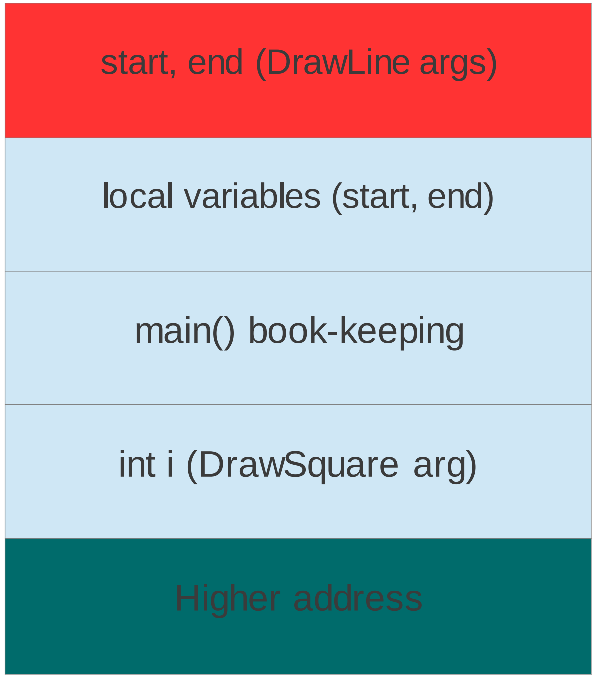
Call Stack

Example:

```
  void DrawSquare(int i){

    int start, end, ...
    DrawLine(start, end);
}
void DrawLine(int start,  int end)
{          //local variables
           ...
   }
```

Lower address

Top of Stack



start, end (DrawLine args)

local variables (start, end)

main() book-keeping

int i (DrawSquare arg)

Higher address

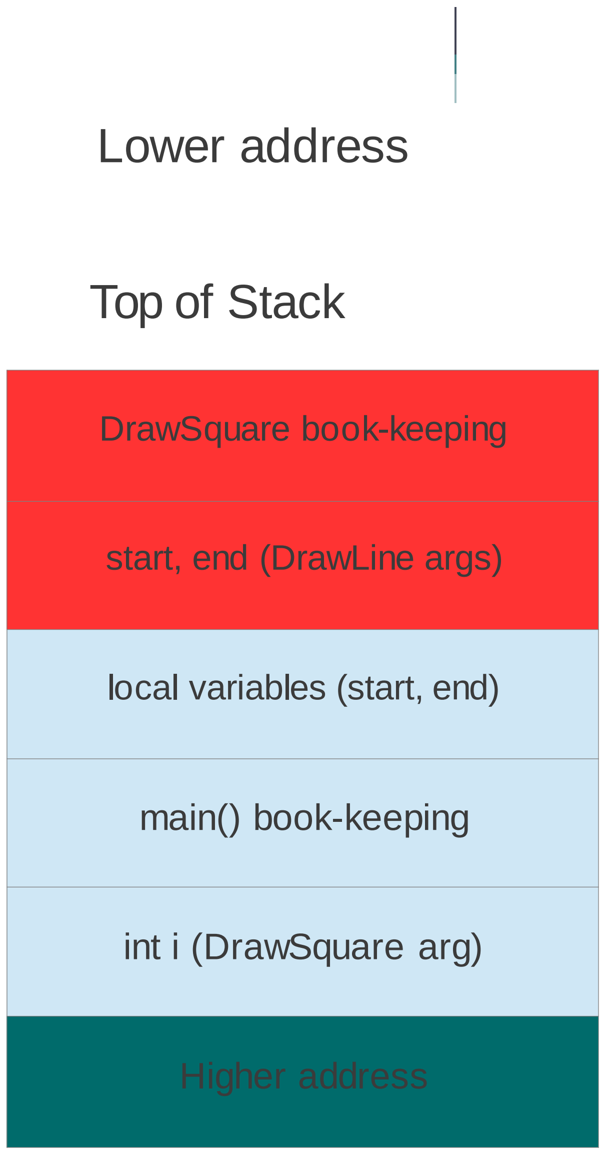
DrawSquare
Stack Frame

Call Stack

Example:

```
  void DrawSquare(int i){
   int start, end, ...
    DrawLine(start, end);
}
void DrawLine(int start,  int end)
{       //local
        variables

        ...

     }
```

DrawSquare Stack Frame



Lower address

Top of Stack

DrawSquare book-keeping

start, end (DrawLine args)

local variables (start, end)

main() book-keeping

int i (DrawSquare arg)

Higher address

Call Stack

Example:

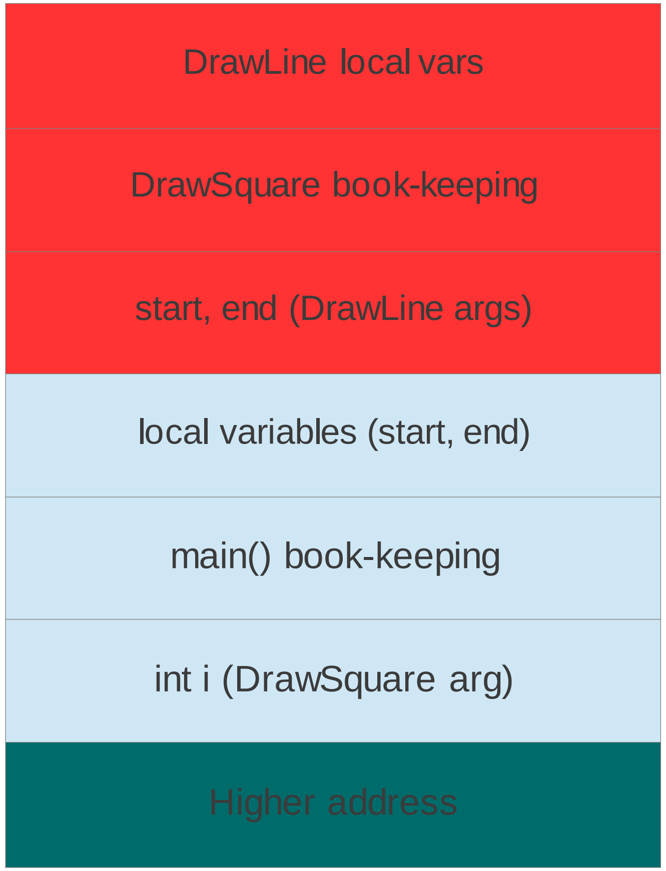
```
 void DrawSquare(int i){

   int start, end, ...
    DrawLine(start, end);

}



void DrawLine(int start,  int end){

//local variables


      ...
}
```

Lower address

Top of Stack

DrawLine Stack Frame

DrawSquare Stack Frame



DrawLine local vars

DrawSquare book-keeping

start, end (DrawLine args)

local variables (start, end)

main() book-keeping

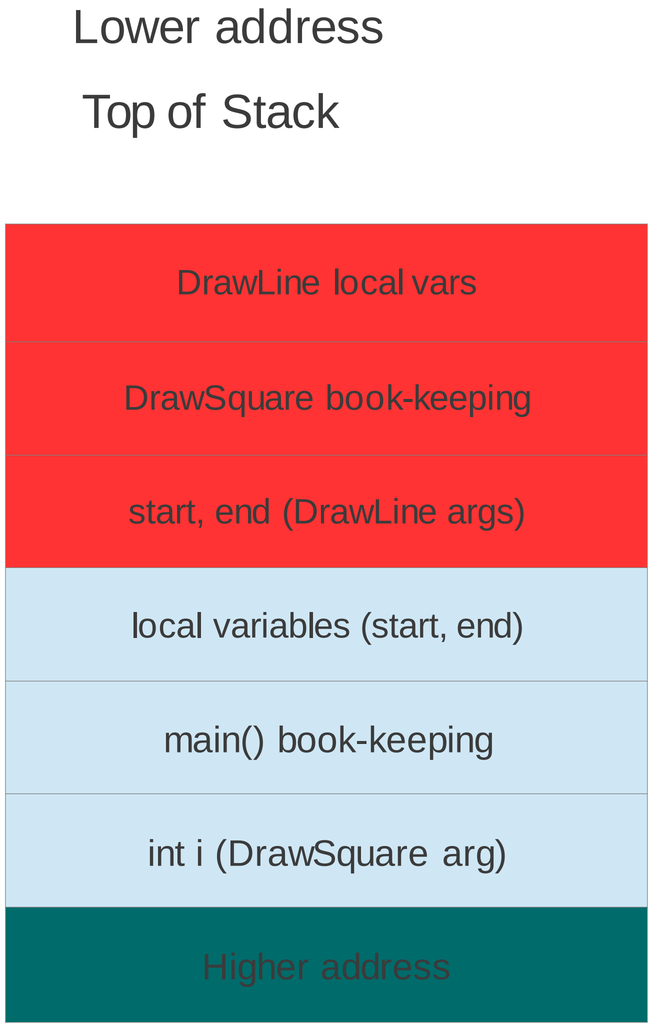
int i (DrawSquare arg)

Higher address

Call Stack

Example: DrawLine returns

```
void DrawSquare(int i){
int start, end, ...
DrawLine(start, end);
}

void DrawLine(int start,  int end){


   //local variables
        ...
}
```



Lower address

Top of Stack

DrawLine local vars

DrawSquare book-keeping

start, end (DrawLine args)

local variables (start, end)

main() book-keeping

int i (DrawSquare arg)

Higher address

DrawLine Stack Frame

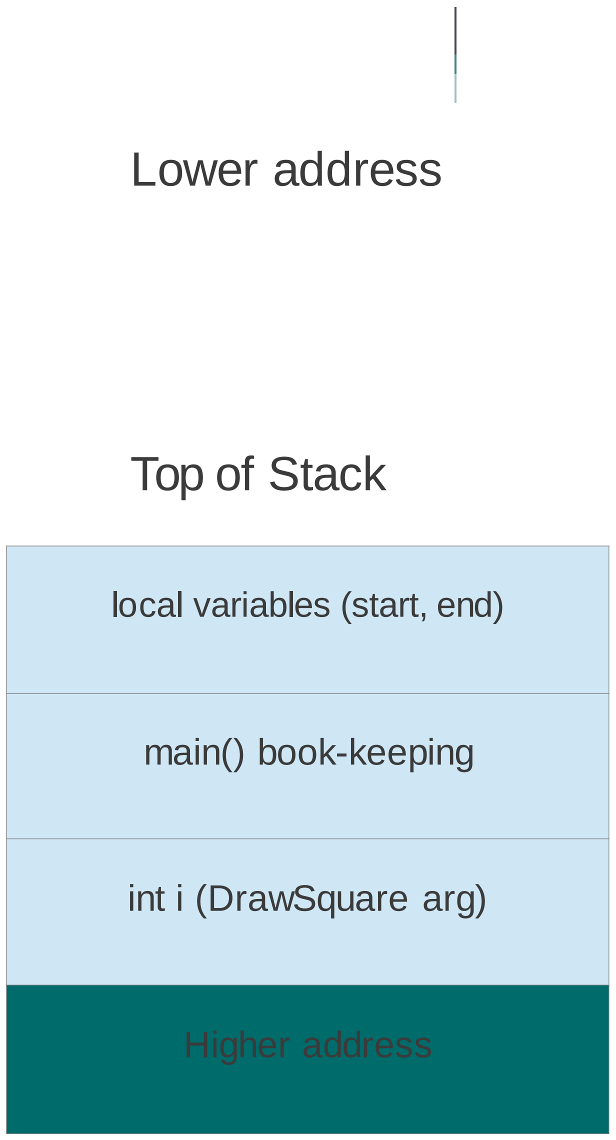
DrawSquare Stack Frame

Call Stack

Example: DrawLine returns

```
  void DrawSquare(int i){
   int start, end, ...
    DrawLine(start, end);
}
void DrawLine(int start,  int end)
{

        //local variables
        ...
}
```

DrawSquare
Stack Frame



Lower address

Top of Stack

local variables (start, end)

main() book-keeping

int i (DrawSquare arg)

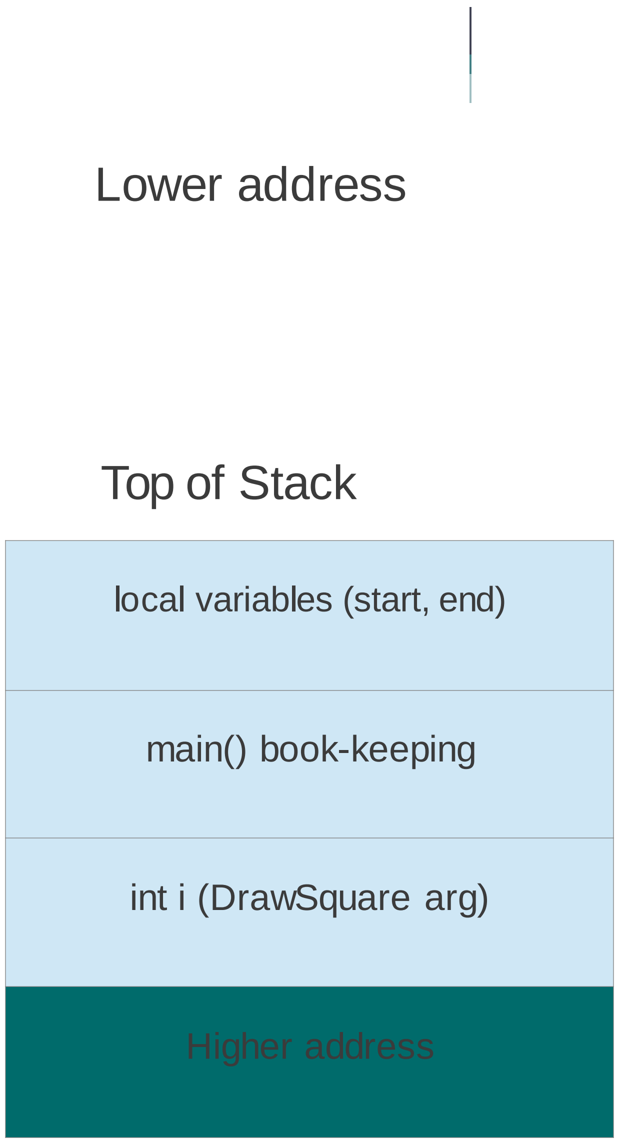
Higher address

Call Stack

Example: DrawSquare returns

```
  void DrawSquare(int i){
   int start, end, ...
   DrawLine(start, end);
}
void DrawLine(int start,  int end){
        //local variables
        ...

}
```

DrawSquare
Stack frame



Lower address

Top of Stack

local variables (start, end)

main() book-keeping

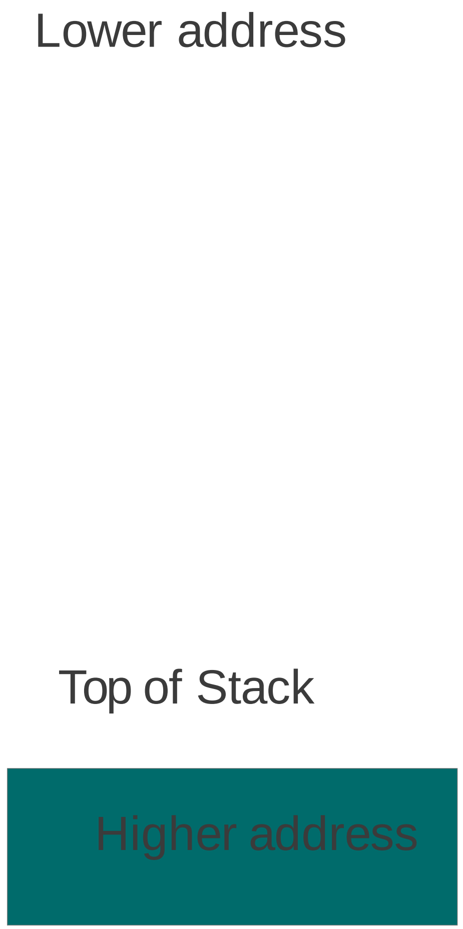
int i (DrawSquare arg)

Higher address

Call Stack

Example: DrawSquare returns

```
void DrawSquare(int i){  int start, end,
...
    DrawLine(start, end);
}
void DrawLine(int start,  int end){
    //local variables
    ...
    }
```



Lower address

Top of Stack

Higher address

Pointers

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Arrays and Pointers in C

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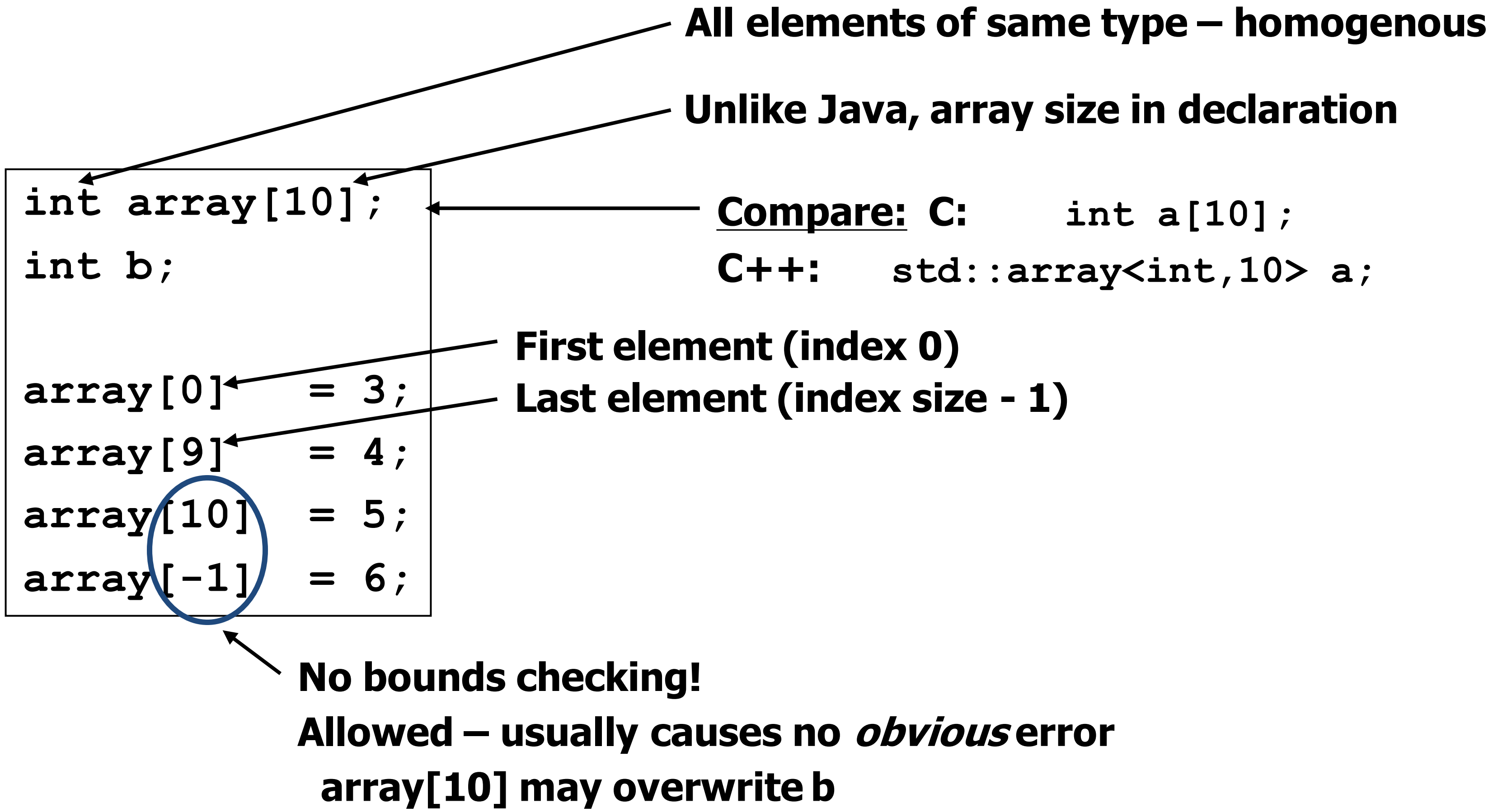
Objectives

Be able to use arrays, pointers, and strings in C programs

Be able to explain the representation of these data types at the machine level, including their similarities and differences

Arrays in C



All elements of same type – homogenous

Unlike Java, array size in declaration

```
int array[10];
int b;

array[0]    = 3;
array[9]    = 4;
array[10]   = 5;
array[-1]   = 6;
```

Compare: C: `int a[10];`

C++: `std::array<int,10> a;`

First element (index 0)

Last element (index size - 1)

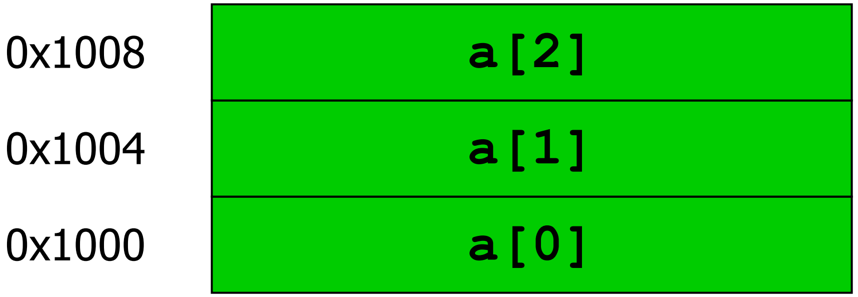
No bounds checking!

Allowed – usually causes no *obvious* error

array[10] may overwrite b

Array Representation

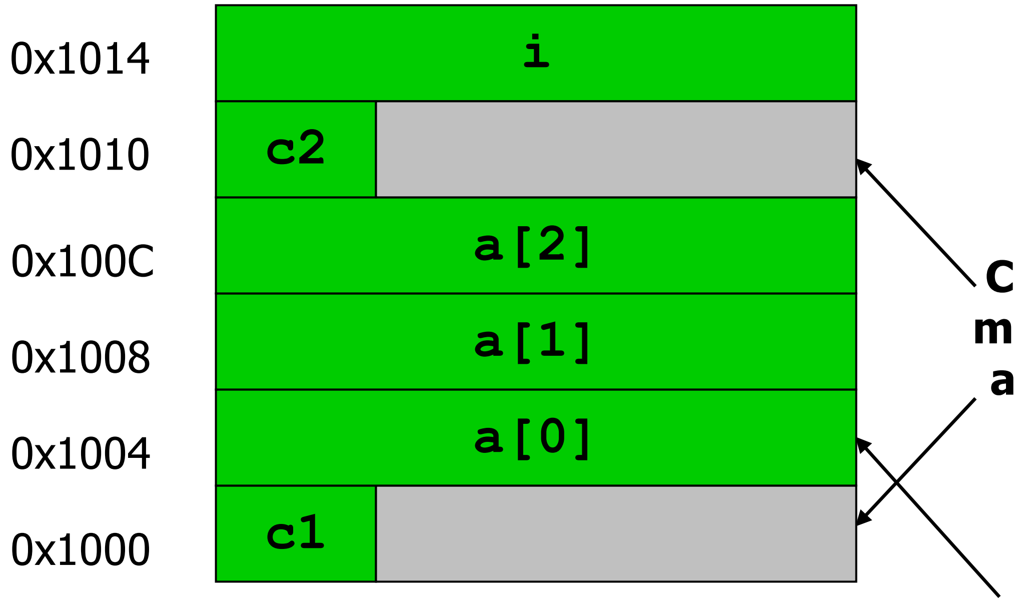
- Homogeneous → Each element same size – s bytes
  - An array of m data values is a sequence of m×s bytes
  - Indexing: 0th value at byte s×0, 1st value at byte s×1, …
- m and s are not part of representation
  - Unlike in some other languages
  - s known by compiler – usually irrelevant to programmer
  - m often known by compiler – if not, must be saved by programmer



```
int a[3];
```

Array Representation

```
char    c1;
int     a[3];
char    c2;
int     i;
```



Could be optimized by making these adjacent, and reducing padding (by default, not)

Array aligned by size of elements

Array Sizes

```
int  array[10];
```

- What is

4

returns the size of an object in bytes

- `sizeof(array[3])`?

40

- `sizeof(array)`?

Multi-Dimensional Arrays

```
int  matrix[2][3];

matrix[1][0] = 17;
```

0x1014	`matrix[1][2]`
0x1010	`matrix[1][1]`
0x100C	`matrix[1][0]`
0x1008	`matrix[0][2]`
0x1004	`matrix[0][1]`
0x1000	`matrix[0][0]`

Recall: no bounds checking

What happens when you write:

```
  matrix[0][3] = 42;
```

"Row Major"
Organization

Variable-Length Arrays

```
int
function(int n)
{
    int  array[n];
    …
```

New C99 feature: Variable-length arrays defined within functions

Global arrays must still have fixed (constant) length

Memory Addresses

- Storage cells are typically viewed as being byte-sized
  - Usually the smallest addressable unit of memory
    - Few machines can directly address bits individually
  - Such addresses are sometimes called *byte-addresses*
- Memory is often accessed as words
  - Usually a word is the largest unit of memory access by a single machine instruction
    - CLEAR's word size is 8 bytes (= `sizeof(long)`)
  - A *word-address* is simply the byte-address of the word's first byte

Pointers

- Special case of bounded-size natural numbers
  - Maximum memory limited by processor word-size
  - 2^{32} bytes = 4GB, 2^{64} bytes = 16 exabytes
- A pointer is just another kind of value
  - A basic type in C

```
int *ptr;
```

The variable “ptr” stores a pointer to an “int”.

Pointer Operations in C

- Creation

  & *variable* Returns variable's memory address

- Dereference

  * *pointer* Returns contents stored at address

- Indirect assignment

  * *pointer* = *val* Stores value at address

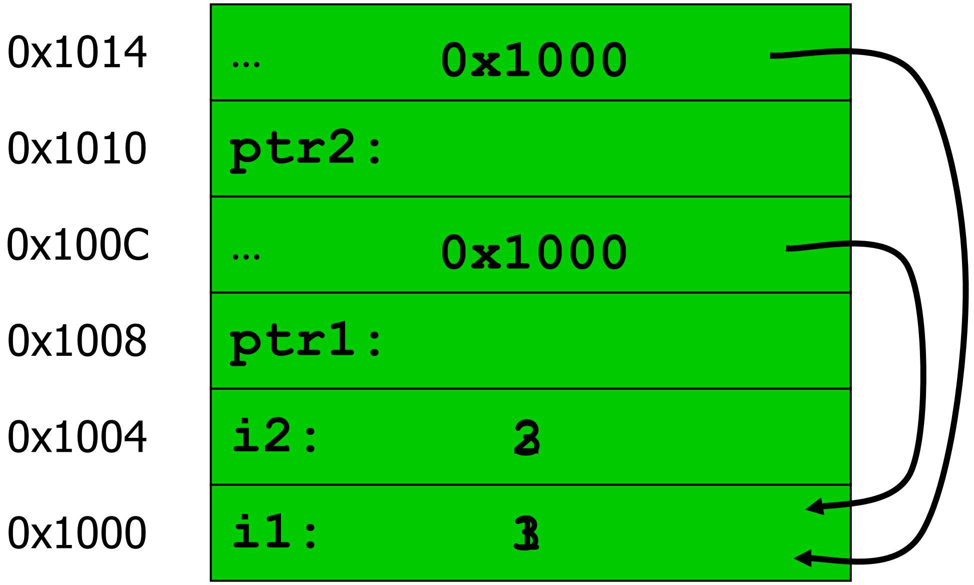
- Of course, still have...

- Assignment

  pointer = *ptr* Stores pointer in another variable

Using Pointers

```
int  i1;
int  i2;
int *ptr1;
int *ptr2;

i1 = 1;
i2 = 2;

ptr1 = &i1;
ptr2 = ptr1;

*ptr1 = 3;
i2 = *ptr2;
```



Using Pointers (cont.)

```
int  int1     = 1036;   /* some data to point to  */
int  int2     = 8;

int *int_ptr1 = &int1;  /* get addresses of data  */
int *int_ptr2 = &int2;

*int_ptr1 = int_ptr2;

*int_ptr1 = int2;
```

What happens?

Type check warning: `int_ptr2` **is not an** `int`

`int1` **becomes 8**

Using Pointers (cont.)

```
int  int1     = 1036;   /* some data to point to  */
int  int2     = 8;

int *int_ptr1 = &int1;  /* get addresses of data  */
int *int_ptr2 = &int2;

int_ptr1 = *int_ptr2;

int_ptr1 = int_ptr2;
```

What happens?

Type check warning: `*int_ptr2` **is not an** `int *`

Changes `int_ptr1` **– doesn’t change** `int1`

Pointer Arithmetic

pointer + *number* *pointer* – *number*

E.g., *pointer* + `1` adds 1 <u>something</u> to a pointer

```
char    *p;
char     a;
char     b;

p = &a;
p += 1;
```

```
int     *p;
int      a;
int      b;

p = &a;
p += 1;
```

In each, p now points to b
(Assuming compiler doesn’t reorder variables in memory)

Adds 1*sizeof(char) to the memory address

Adds 1*sizeof(int) to the memory address

Pointer arithmetic should be used <u>cautiously</u>

A Special Pointer in C

- Special constant pointer `NULL`
  - Points to no data
  - Dereferencing illegal – causes *segmentation fault*

  - To define, include `<stdlib.h>` or `<stdio.h>`

Generic Pointers

- void *: a “pointer to anything”

```
void   *p;
int     i;
char    c;
p = &i;
p = &c;
putchar(*(char *)p);
```

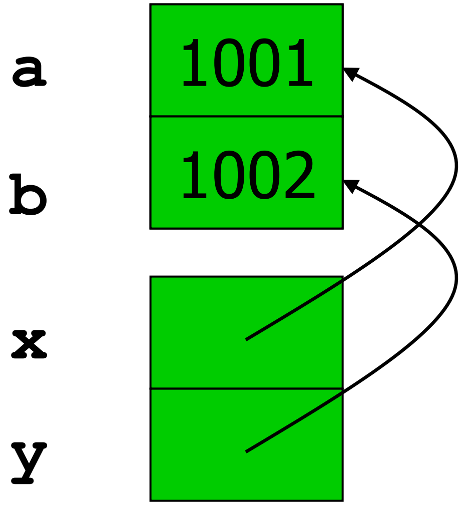
type cast: tells the compiler to “change” an object’s type (for type checking purposes – does not modify the object in any way)

Dangerous! Sometimes necessary…

- Lose all information about what type of thing is pointed to
  - Reduces effectiveness of compiler’s type-checking
  - Can’t use pointer arithmetic

Pass-by-Reference

```
void
set_x_and_y(int *x, int *y)
{

   *x = 1001;
   *y = 1002;
}

void
f(void)
{
   int a = 1;
   int b = 2;

   set_x_and_y(&a, &b);
}
```



Arrays and Pointers

- Dirty "secret":

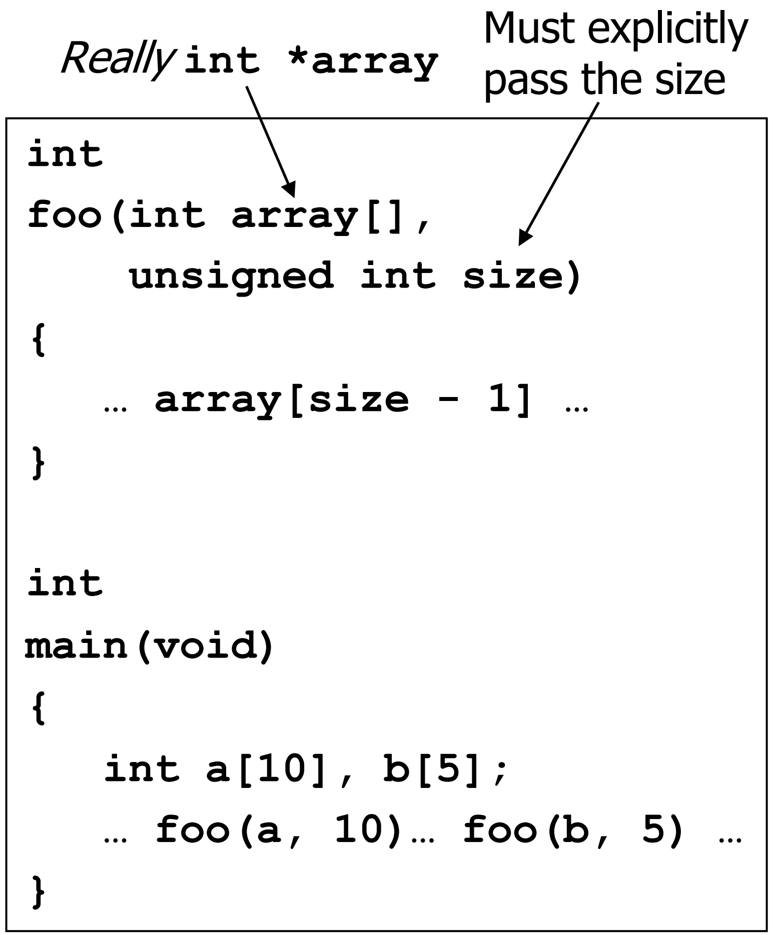
- Array name ≈ a pointer to the initial (0th) array element

```
a[i]  ≡  *(a + i)
```

- An array is passed to a function as a pointer
  - The array size is lost!

- Usually bad style to interchange arrays and pointers
  - Avoid pointer arithmetic!

Passing arrays:



Really **int *array**

Must explicitly pass the size

```
int
foo(int array[],
    unsigned int size)
{
   … array[size - 1] …
}

int
main(void)
{
   int a[10], b[5];
   … foo(a, 10)… foo(b, 5)  …
}
```

Arrays and Pointers

```
int
foo(int array[],
    unsigned int size)
{
   …
   printf(“%d\n”, sizeof(array));
}

int
main(void)
{
   int a[10], b[5];
   … foo(a, 10)… foo(b, 5) …
   printf(“%d\n”, sizeof(a));
}
```

What does this print? **8**

... because `array` is really a pointer

What does this print? **40**

Arrays and Pointers

```
int  i;
int  array[10];

for (i = 0; i < 10; i++) {
  …
  array[i] = …;
  …
}
```

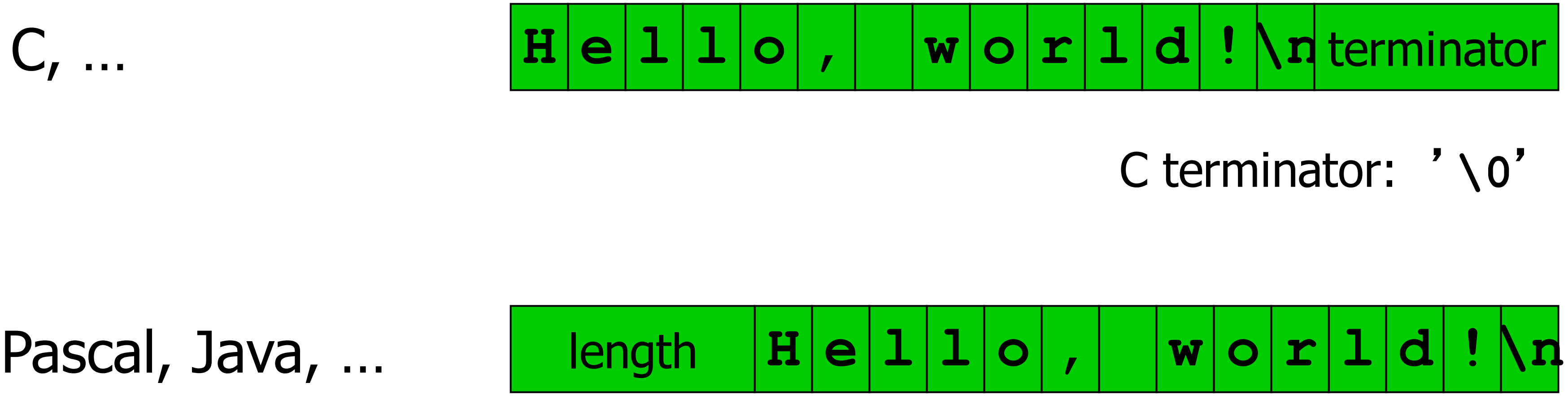
```
int *p;
int  array[10];

for (p = array; p < &array[10]; p++) {
  …
  *p = …;
  …
}
```

These two blocks of code are functionally equivalent

Strings

- In C, strings are just an array of characters
  - Terminated with ‘\0’ character
  - Arrays for bounded-length strings
  - Pointer for constant strings (or unknown length)

```
char  str1[15] = “Hello, world!\n”;
char *str2      = “Hello, world!\n”;
```



C, …

H	e	l	l	o	,		w	o	r	l	d	!	\n	terminator

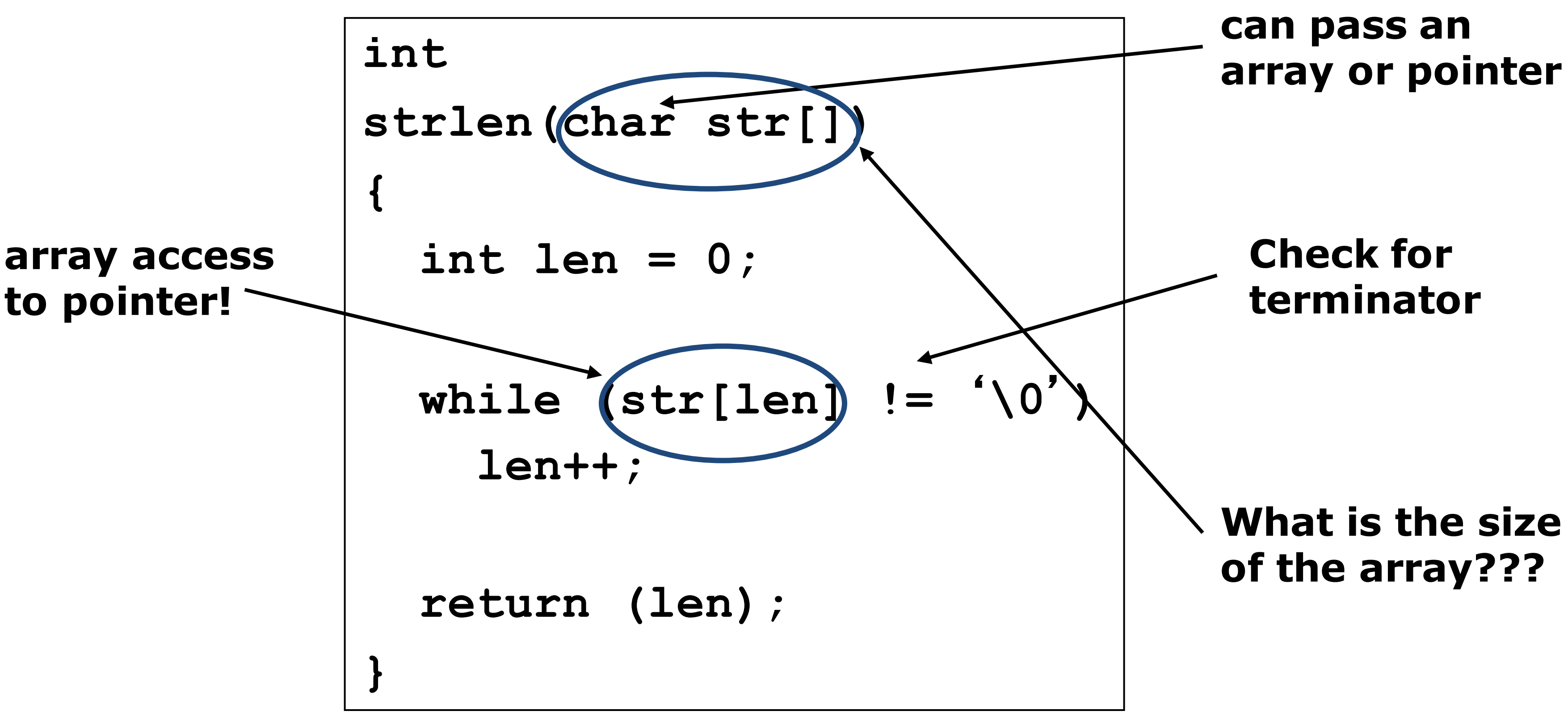
C terminator: ’\0’

Pascal, Java, …

length	H	e	l	l	o	,		w	o	r	l	d	!	\n

String length

- Must calculate length:



```
int
strlen(char str[])
{
  int len = 0;

  while (str[len] != ‘\0’)
    len++;

  return (len);
}
```

can pass an array or pointer

array access to pointer!

Check for terminator

What is the size of the array???

- Provided by standard C library: `#include <string.h>`

Pointer to Pointer (char **argv)

Passing arguments to main:

```
int
main(int argc, char **argv)
{
   ...
}
```

size of the argv array/vector

an array/vector of char *

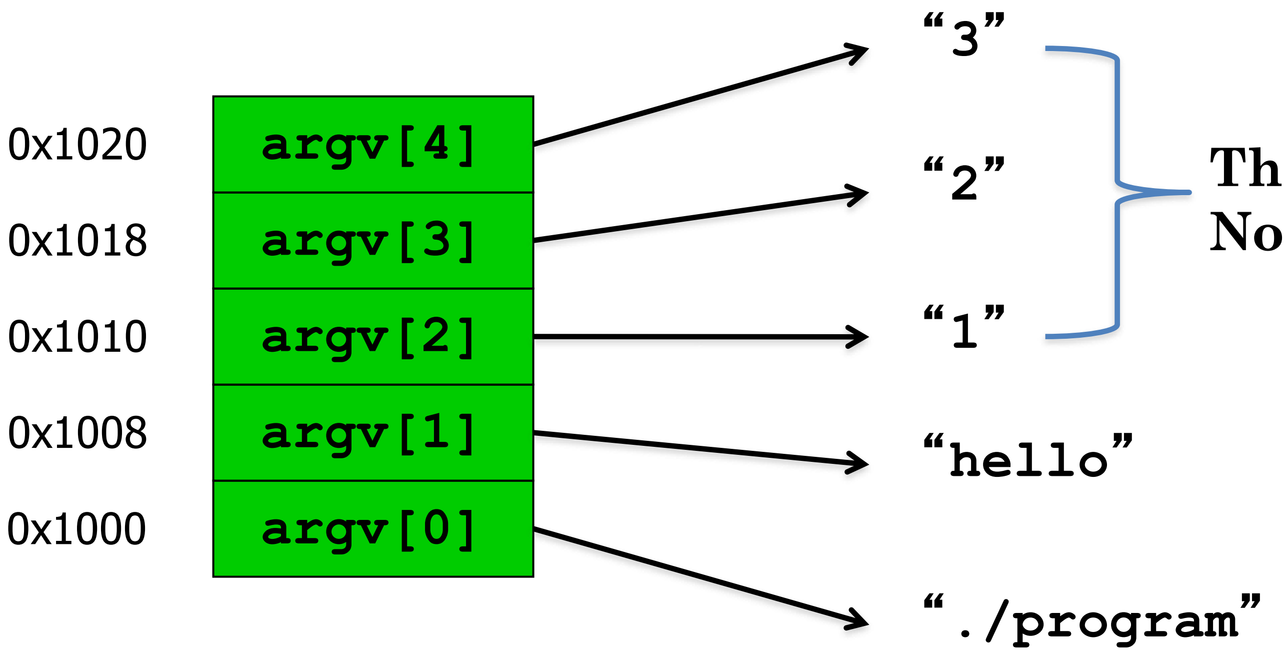
Recall when passing an array, a pointer to the first element is passed

Suppose you run the program this way

```
UNIX% ./program hello 1 2 3
```

`argc == 5` (five strings on the command line)

char **argv



0x1020	argv[4]
0x1018	argv[3]
0x1010	argv[2]
0x1008	argv[1]
0x1000	argv[0]

These are strings!!
Not integers!