

COMP201

Computer Systems & Programming

Lecture #8 – The Stack and The Heap

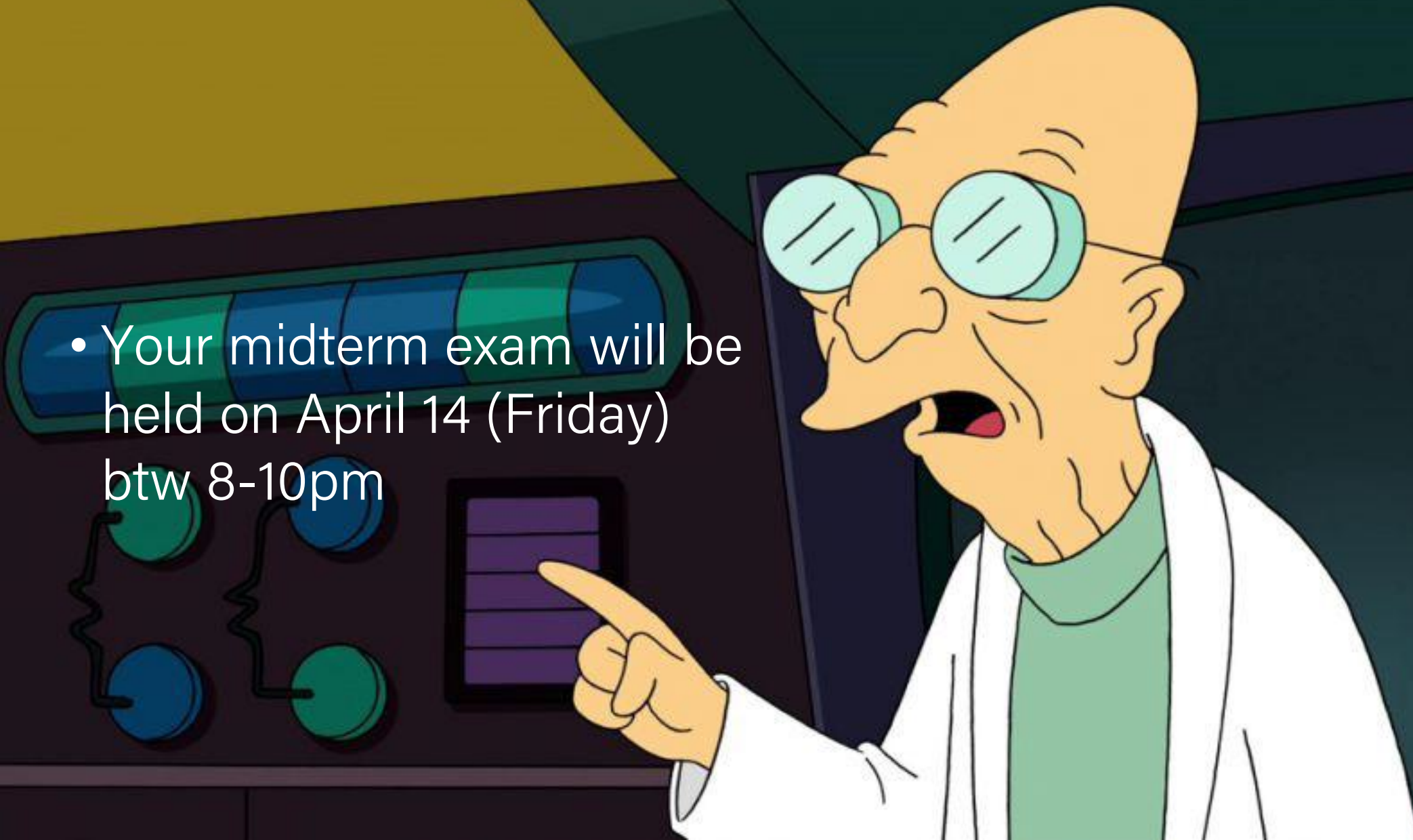


KOÇ
UNIVERSITY

Aykut Erdem // Koç University // Fall 2023

Good news, everyone!

- Your midterm exam will be held on April 14 (Friday) btw 8-10pm



Pointers Practice

* Wars: Episode I (of 2)

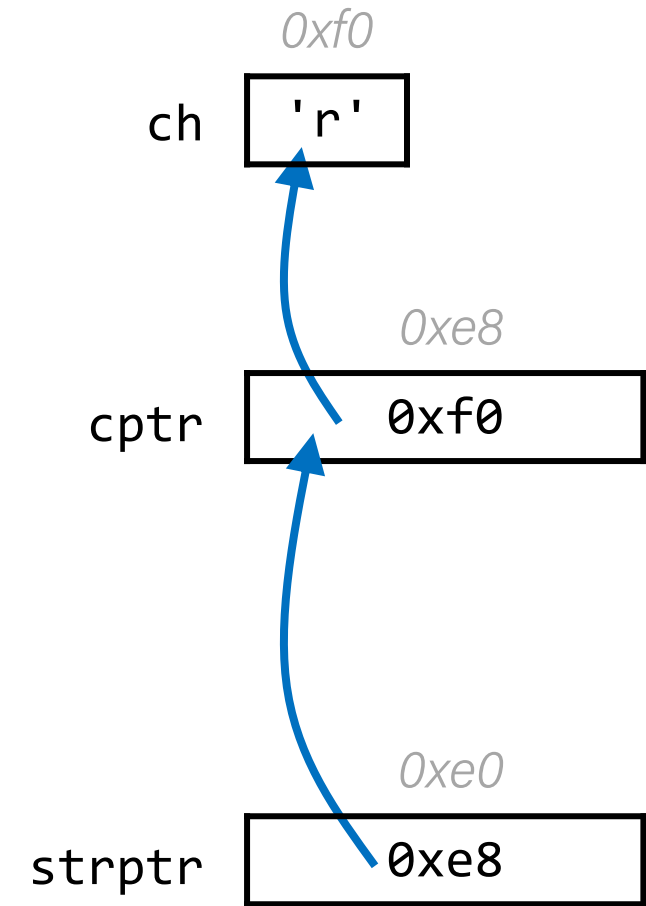
Review

In variable declaration, * creates a **pointer**.

`char ch = 'r';` ch stores a char

`char *_cptr = &ch;` cptr stores an address
of a char
(**points to** a char)

`char **_strptr = &cptr;` strptr stores an address
of a char *
(**points to** a char *)



* Wars: Episode II (of 2)

Review

In reading values from/storing values, * dereferences a pointer.

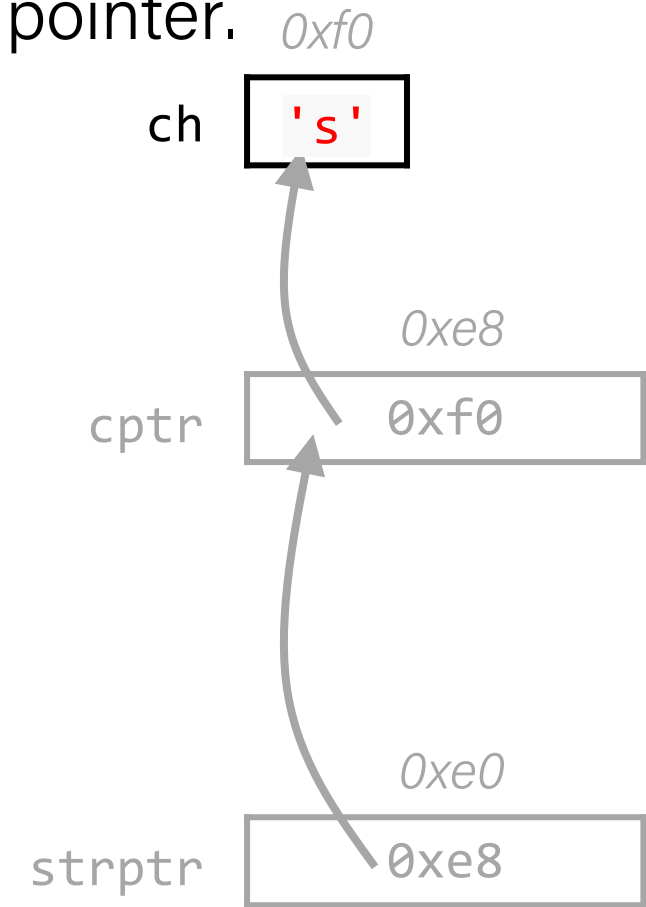
```
char ch = 'r';
```

```
ch = ch + 1;
```

```
char *cptr = &ch;
```

```
char **strptr = &cptr;
```

Increment value stored in ch



* Wars: Episode II (of 2)

Review

In reading values from/storing values, * dereferences a pointer.

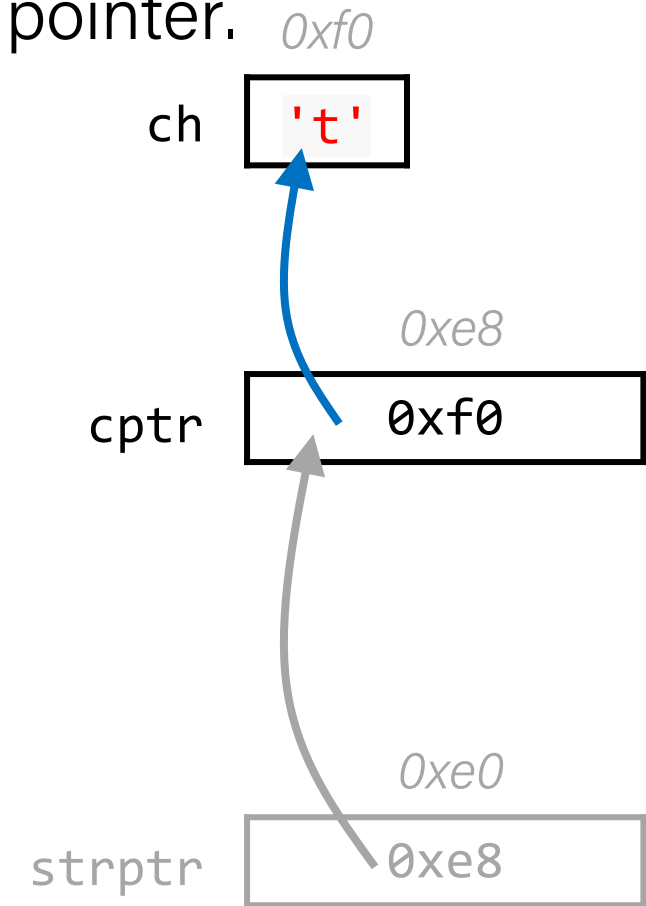
```
char ch = 'r';  
ch = ch + 1;
```

Increment value stored in ch

```
char *cptr = &ch;  
*cptr = *cptr + 1;
```

Increment value stored at
memory address in cptr
(increment char **pointed to**)

```
char **strptr = &cptr;
```



* Wars: Episode II (of 2)

Review

In reading values from/storing values, * dereferences a pointer.

```
char ch = 'r';  
ch = ch + 1;
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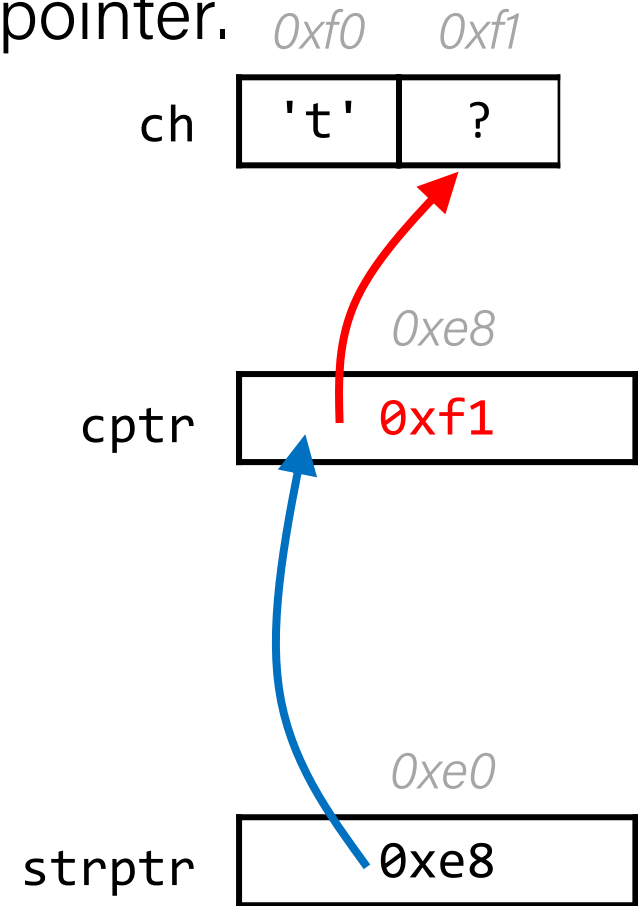
Increment value stored in ch

```
char *cptr = &ch;  
*cptr = *cptr + 1;
```

Increment value stored at
memory address in cptr
(increment char **pointed to**)

```
char *_strptr = &cptr;  
*strptr = *strptr + 1;
```

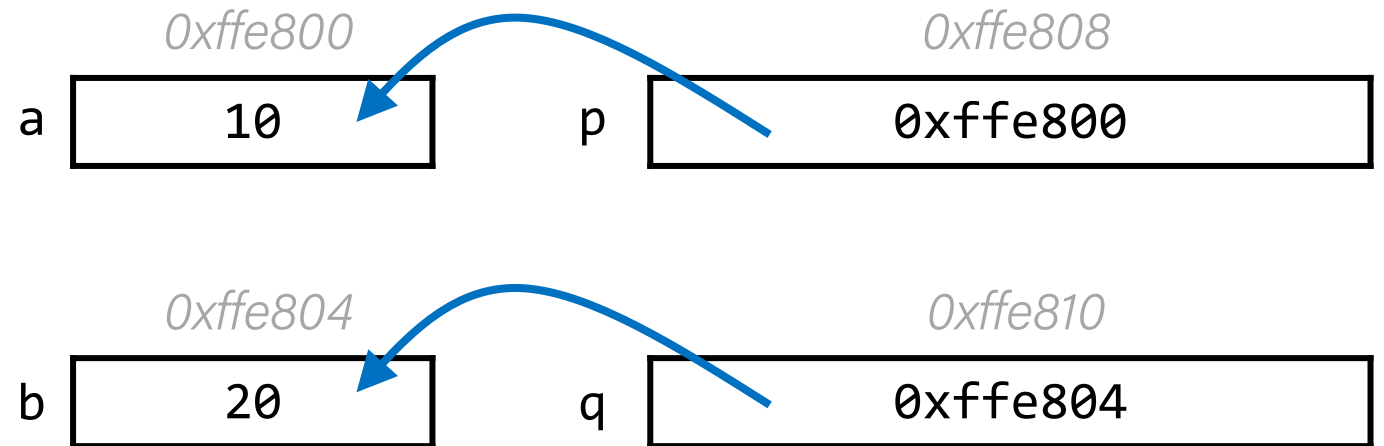
Increment value stored at
memory address in cptr
(increment address **pointed to**)



Pen and paper: A * Wars Story

```
1 void binky() {  
2     int a = 10;  
3     int b = 20;  
4     int *p = &a;  
5     int *q = &b;  
6  
7     *p = *q;  
8     p = q;  
9 }
```

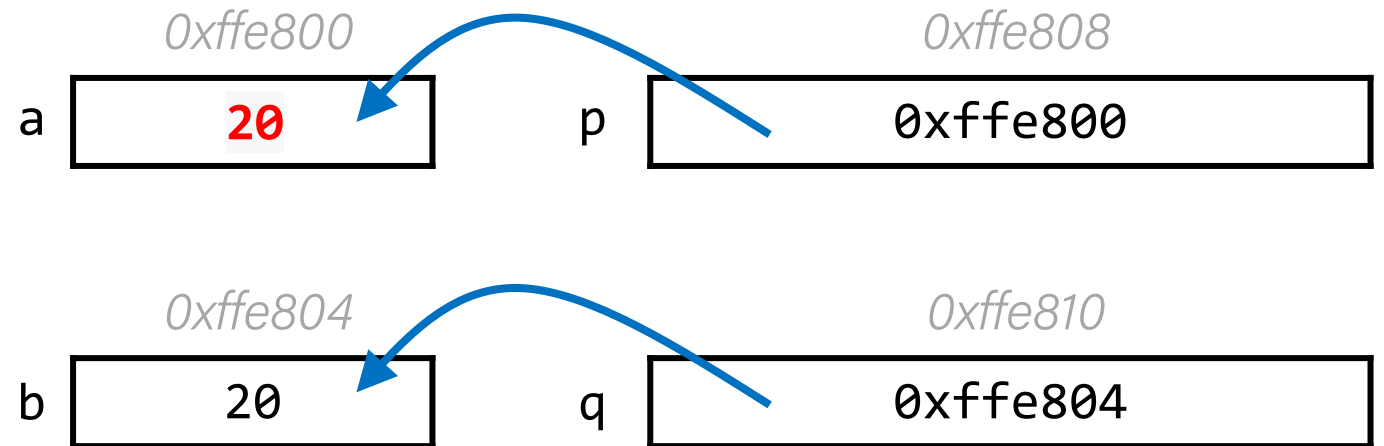
- Lines 2-5: Draw a diagram.
- Line 7: Update your diagram.
- Line 8: Update your diagram.



Pen and paper: A * Wars Story

```
1 void binky() {  
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```

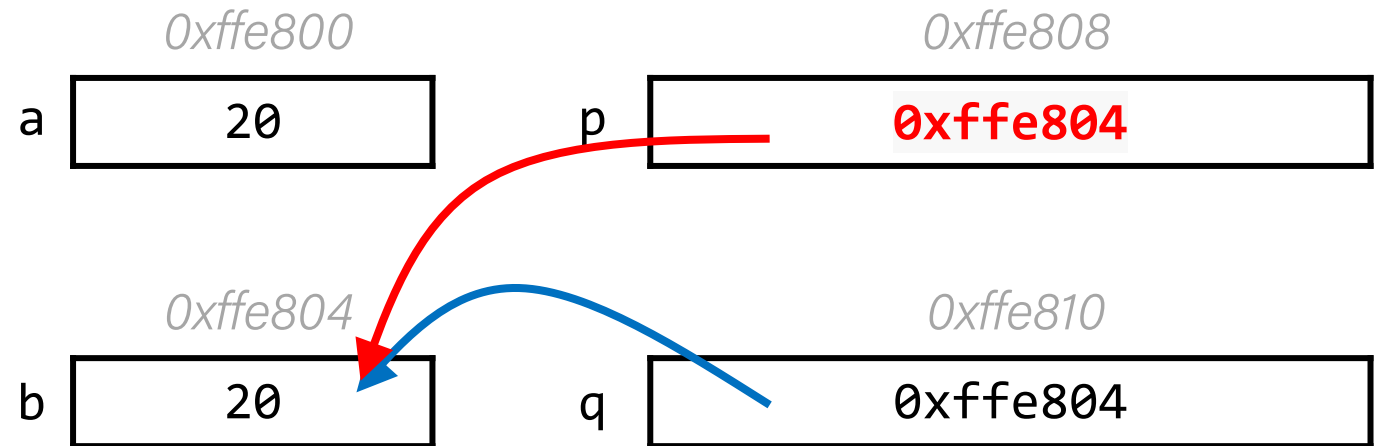
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Pen and paper: A * Wars Story

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- Lines 2-5: Draw a diagram.
- Line 7: Update your diagram.
- Line 8: Update your diagram.



Plan for Today

- Arrays in Memory
- Arrays of Pointers
- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

Disclaimer: Slides for this lecture were borrowed from
—Nick Troccoli's Stanford CS107 class

Lecture Plan

- Arrays in Memory
- Arrays of Pointers
- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

Arrays

When you declare an array, contiguous memory is allocated on the stack to store the contents of the entire array.

```
char str[6];  
strcpy(str, "apple");
```

The array variable (e.g. **str**) is not a pointer; it refers to the entire array contents. In fact, **sizeof** returns the size of the entire array!

```
int arrayBytes = sizeof(str);    // 6
```

STACK	
Address	Value
	...
0x105	'\0'
0x104	'e'
0x103	'l'
0x102	'p'
0x101	'p'
0x100	'a'
	...

str {

Arrays

An array variable refers to an entire block of memory. You cannot reassign an existing array to be equal to a new array.

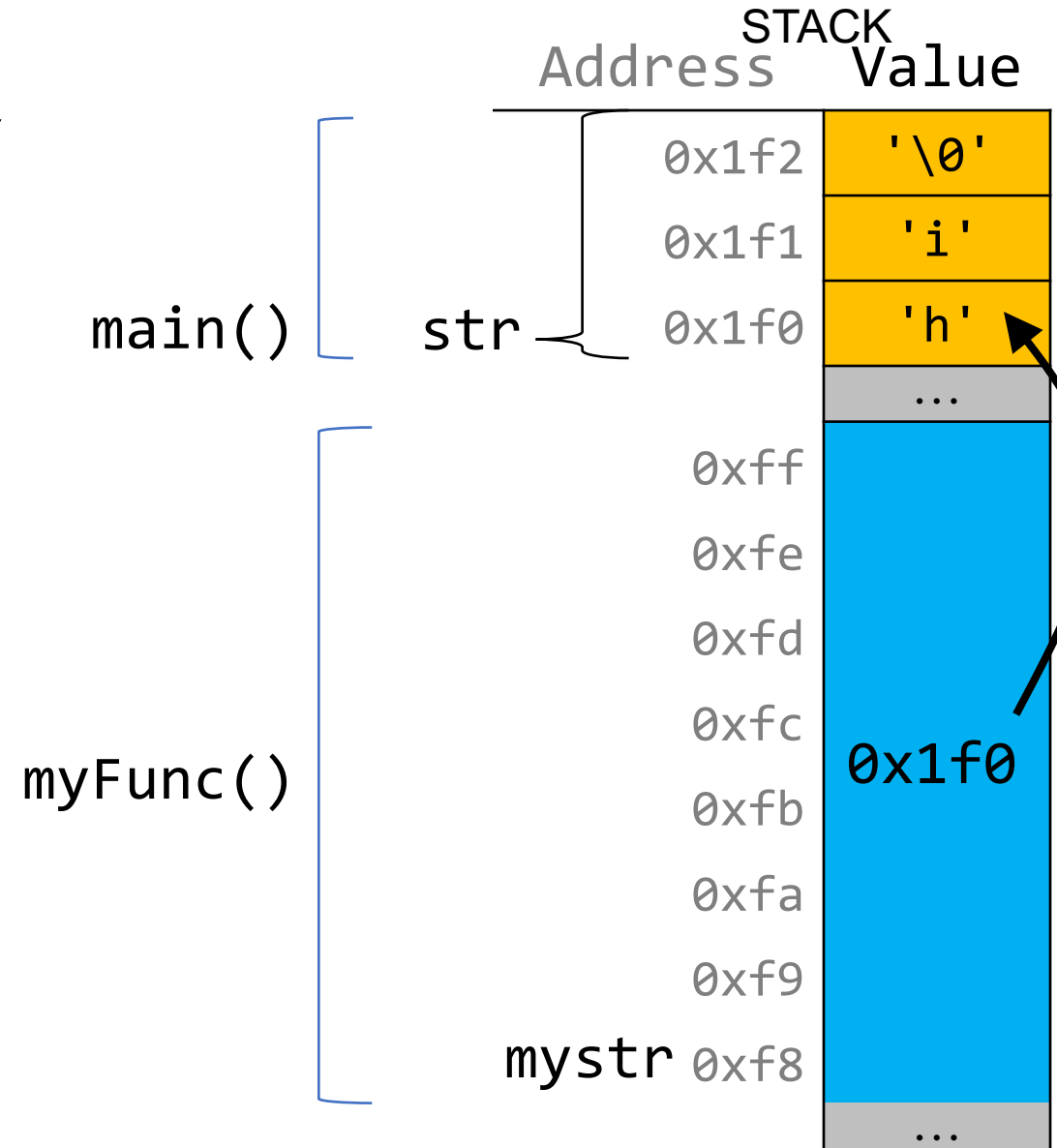
```
int nums[] = {1, 2, 3};  
int nums2[] = {4, 5, 6, 7};  
nums = nums2; // not allowed!
```

An array's size cannot be changed once you create it; you must create another new array instead.

Arrays as Parameters

When you pass an **array** as a parameter, C makes a *copy of the address of the first array element*, and passes it (a pointer) to the function.

```
void myFunc(char *myStr) {  
    ...  
}  
  
int main(int argc, char *argv[]) {  
    char str[3];  
    strcpy(str, "hi");  
    myFunc(str);  
    ...  
}
```

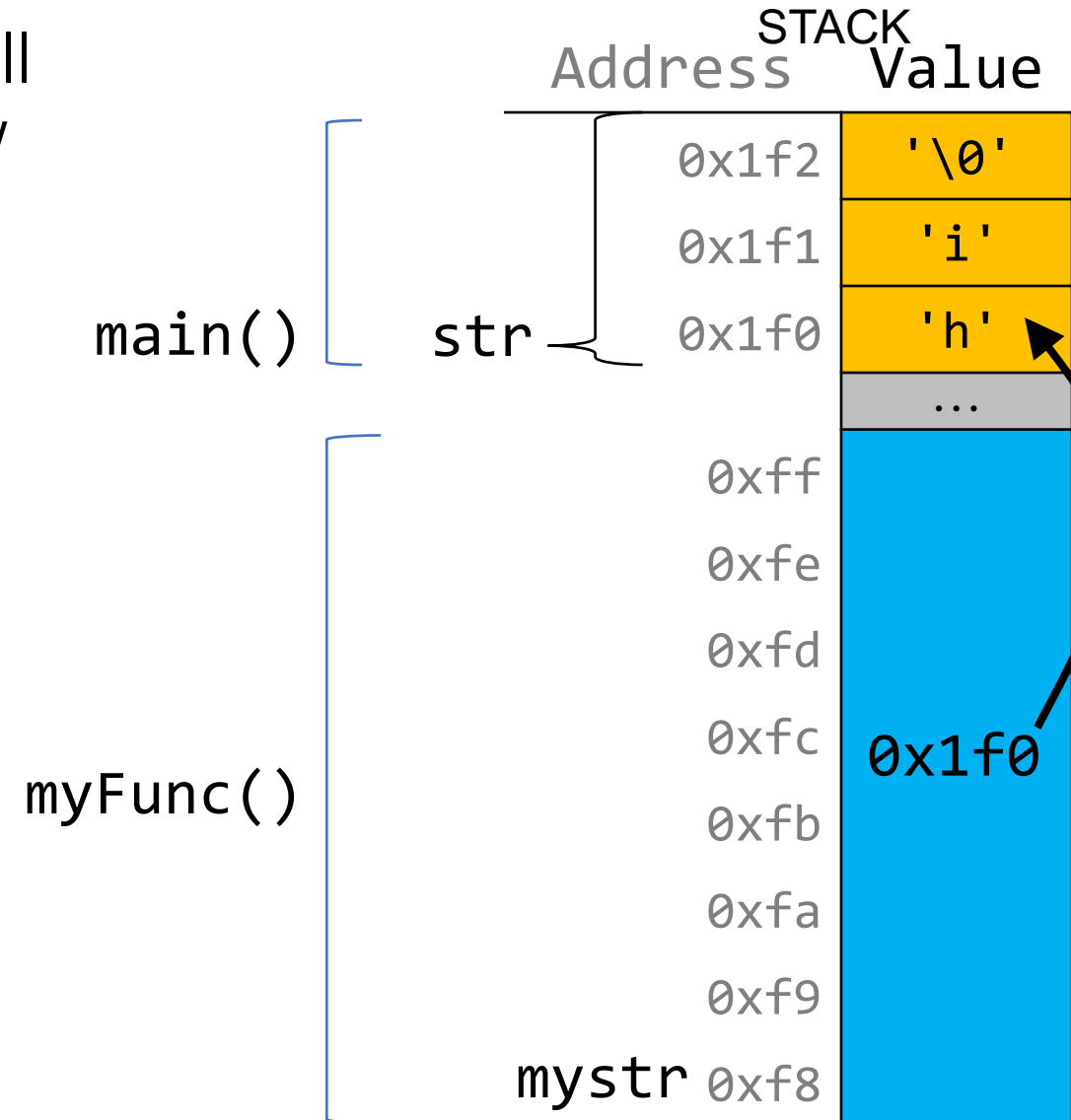


Arrays as Parameters

This also means we can no longer get the full size of the array using **sizeof**, because now it is just a pointer.

```
void myFunc(char *myStr) {  
    int size = sizeof(myStr); // 8  
}
```

```
int main(int argc, char *argv[]) {  
    char str[3];  
    strcpy(str, "hi");  
    int size = sizeof(str); // 3  
    myFunc(str);  
    ...  
}
```



sizeof returns the size of an array, or 8 for a pointer. Therefore, when we pass an array as a parameter, we can no longer use **sizeof** to get its full size.

Lecture Plan

- Arrays in Memory
- Arrays of Pointers
- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

Arrays Of Pointers

You can make an array of pointers to e.g. group multiple strings together:

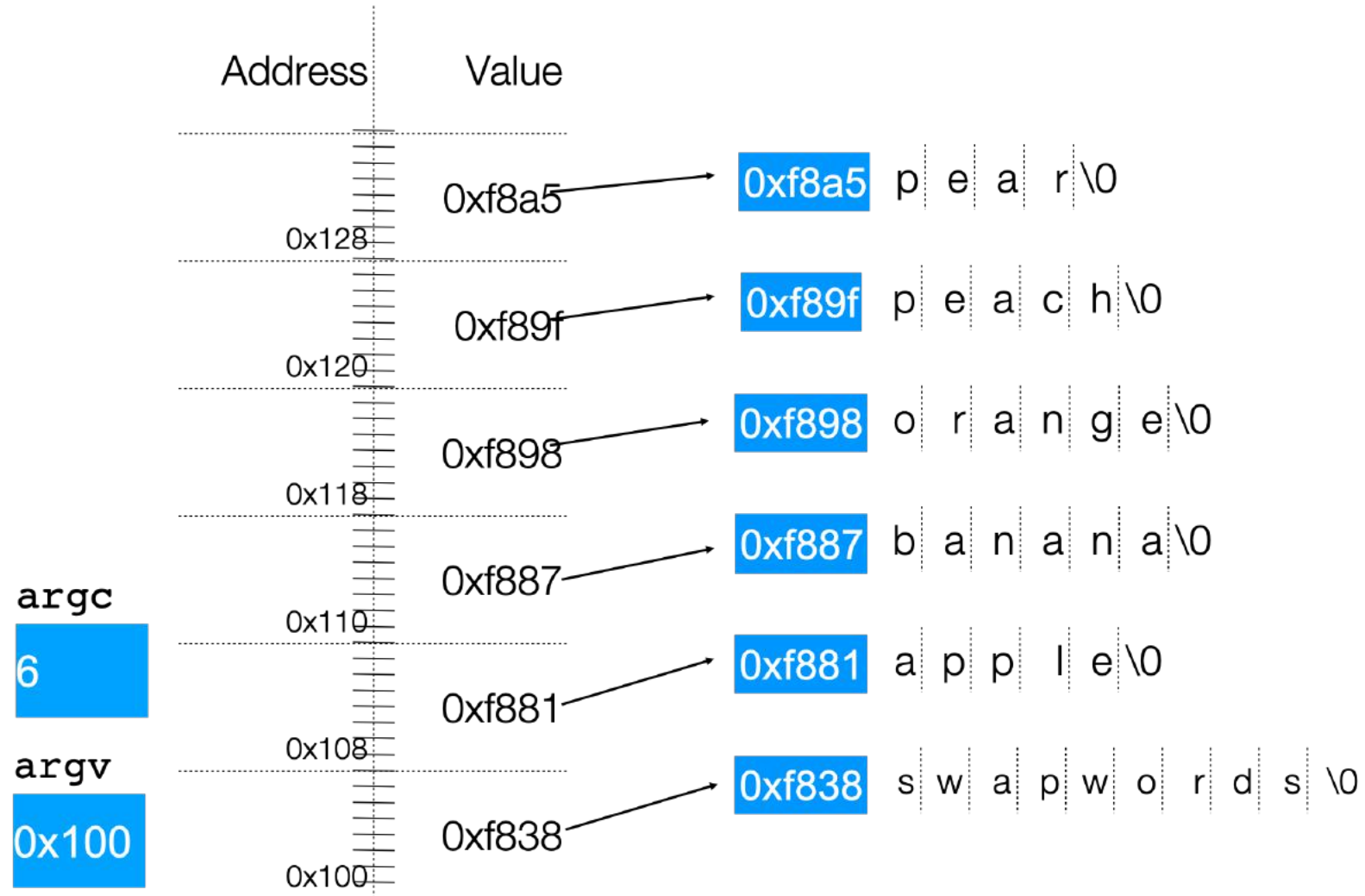
```
char *stringArray[5];    // space to store 5 char *s
```

This stores 5 char *s, *not* all of the characters for 5 strings!

```
char *str0 = stringArray[0];    // first char *
```

Arrays Of Pointers

```
./swapwords apple banana orange peach pear
```



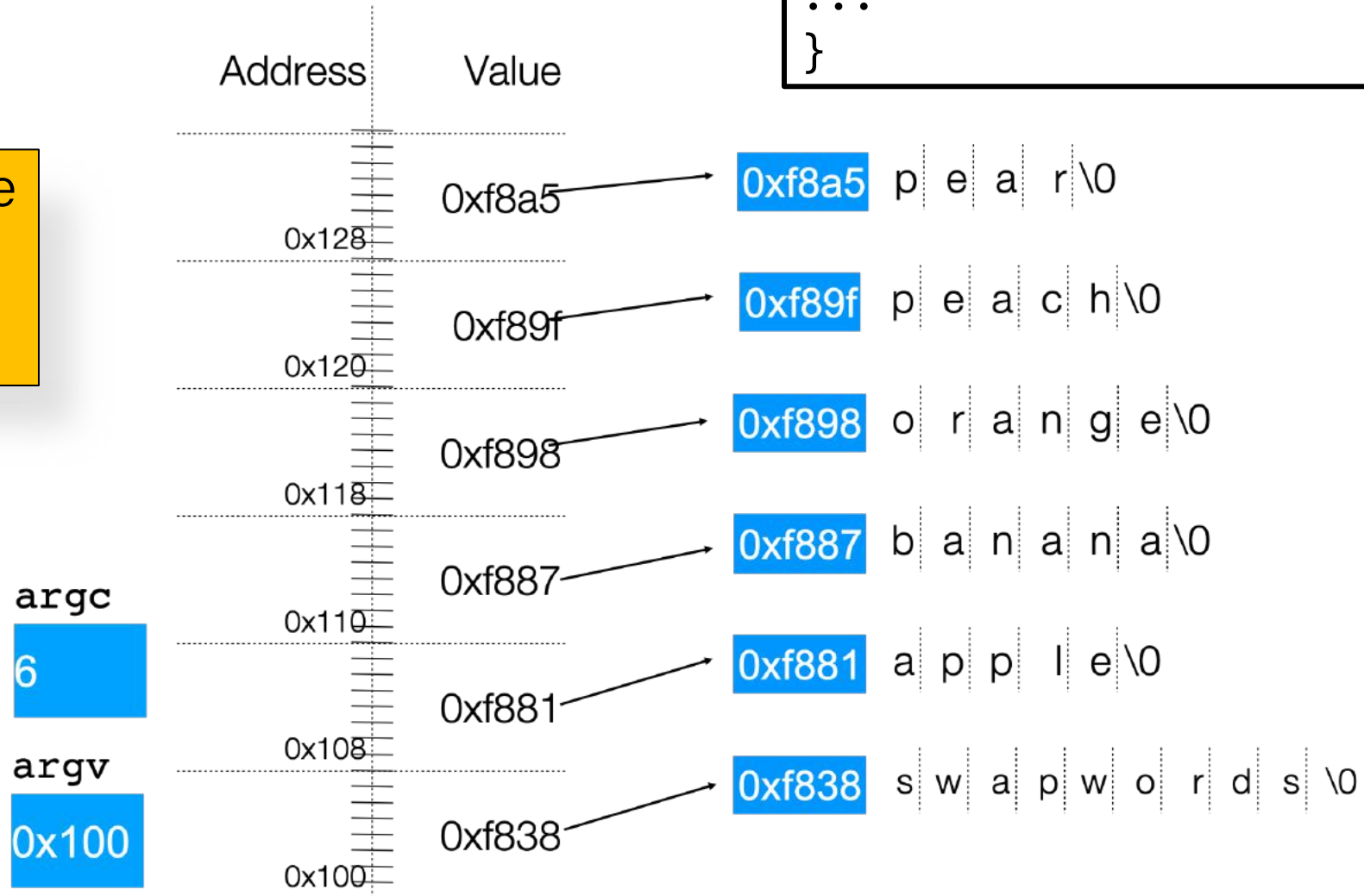
Arrays Of Pointers

```
./swapwords apple banana orange peach pear
```

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

swapwords.c

What is the value of argv[2] in this diagram?



Lecture Plan

- Arrays in Memory
- Arrays of Pointers
- **Pointer Arithmetic**
- The Stack
- The Heap and Dynamic Memory

Pointer Arithmetic

When you do pointer arithmetic, you are adjusting the pointer by a certain *number of places* (e.g. characters).

```
char *str = "apple";           // e.g. 0xff0
char *str1 = str + 1;          // e.g. 0xff1
char *str3 = str + 3;          // e.g. 0xff3

printf("%s", str);              // apple
printf("%s", str1);             // pple
printf("%s", str3);             // le
```

DATA SEGMENT	
Address	Value
	...
0xff5	'\0'
0xff4	'e'
0xff3	'l'
0xff2	'p'
0xff1	'p'
0xff0	'a'
	...

Pointer Arithmetic

Pointer arithmetic does *not* work in bytes. Instead, it works in the *size of the type it points to*.

```
// nums points to an int array
```

```
int *nums = ...           // e.g. 0xff0
```

```
int *nums1 = nums + 1;    // e.g. 0xff4
```

```
int *nums3 = nums + 3;    // e.g. 0xffc
```

```
printf("%d", *nums);      // 52
```

```
printf("%d", *nums1);     // 23
```

```
printf("%d", *nums3);     // 34
```

STACK	
Address	Value
	...
0x1004	1
0x1000	16
0xffc	34
0xff8	12
0xff4	23
0xff0	52
	...

Pointer Arithmetic

When you use bracket notation with a pointer, you are actually *performing pointer arithmetic and dereferencing*:

```
char *str = "apple"; // e.g. 0xff0
```

```
// both of these add two places to str,  
// and then dereference to get the char there.  
// E.g. get memory at 0xff2.
```

```
char thirdLetter = str[2];           // 'p'
```

```
char thirdLetter = *(str + 2);       // 'p'
```

DATA SEGMENT	
Address	Value
	...
0xff5	'\0'
0xff4	'e'
0xff3	'l'
0xff2	'p'
0xff1	'p'
0xff0	'a'
	...

Pointer Arithmetic

Pointer arithmetic with two pointers does *not* give the byte difference. Instead, it gives the number of places they differ by.

```
// nums points to an int array
int *nums = ...           // e.g. 0xff0
int *nums3 = nums + 3;    // e.g. 0xffc
int diff = nums3 - nums;  // 3
```

STACK	
Address	Value
	...
0x1004	1
0x1000	16
0xffc	34
0xff8	12
0xff4	23
0xff0	52
	...

Pointer Arithmetic

How does the code know how many bytes it should look at once it visits an address?

```
int x = 2;
```

```
int *xPtr = &x;           // e.g. 0xff0
```

```
// How does it know to print out just the 4 bytes at xPtr?
```

```
printf("%d", *xPtr);      // 2
```

Pointer Arithmetic

How does the code know how many bytes it should add when performing pointer arithmetic?

```
int nums[] = {1, 2, 3};
```

```
// How does it know to add 4 bytes here?
```

```
int *intPtr = nums + 1;
```

```
char str[6];
```

```
strcpy(str, "COMP201");
```

```
// How does it know to add 1 byte here?
```

```
char *charPtr = str + 1;
```


Pointer Arithmetic

- At compile time, C can figure out the sizes of different data types, and the sizes of what they point to.
- For this reason, when the program runs, it knows the correct number of bytes to address or add/subtract for each data type.

Pointer arithmetic

Array indexing is “syntactic sugar” for pointer arithmetic:

<code>ptr + i</code>	\Leftrightarrow	<code>&ptr[i]</code>
<code>*(ptr + i)</code>	\Leftrightarrow	<code>ptr[i]</code>

⚠ Pointer arithmetic **does not work in bytes**; it works on the type it points to. On `int*` addresses scale by `sizeof(int)`, on `char*` scale by `sizeof(char)`.

- This means too-large/negative subscripts will compile ☺

`arr[99]`

`arr[-1]`

- You can use either syntax on either pointer or array.

Example: Pointer arithmetic

```
1 void func(char *str) {
2     str[0] = 'S';
3     str++;
4     *str = 'u';
5     str = str + 3;
6     str[-2] = 'm';
7 }
8 int main(int argc, const char *argv[]) {
9     char buf[] = "Monday";
10    printf("before func: %s\n", buf);
11    func(buf);
12    printf("after  func: %s\n", buf);
13    return 0;
14 }
```

- Will there be a compile error/segfault?
- If no errors, what is printed?

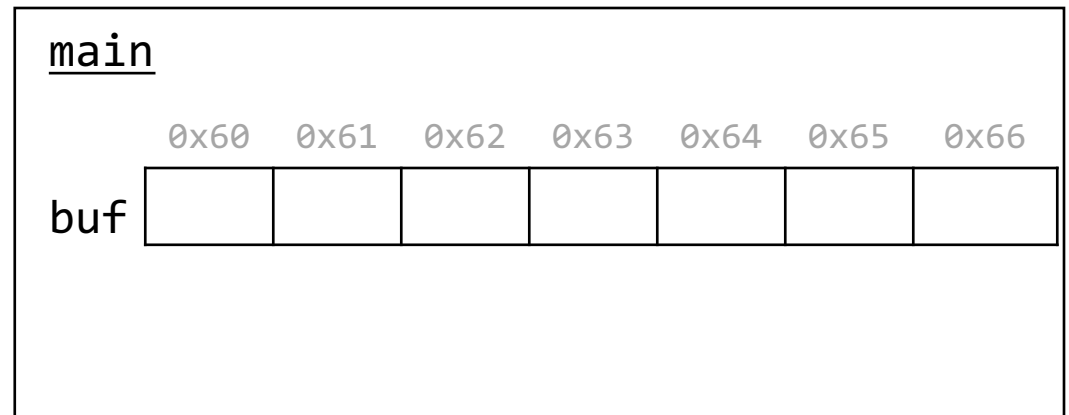
- **Draw memory diagrams!**
- **Pointers** store addresses! Make up addresses if it helps your mental model.



Example: Pointer arithmetic

```
1 void func(char *str) {  
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3     str++;  
4     *str = 'u';  
5     str = str + 3;  
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7 }
```

```
8 int main(int argc, const char *argv[]) {  
9     char buf[] = "Monday";  
10    printf("before func: %s\n", buf);  
11    func(buf);  
12    printf("after  func: %s\n", buf);  
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14 }
```



- **Draw memory diagrams!**
- **Pointers** store addresses! Make up addresses if it helps your mental model.

Code study: strncpy

STRCPY(3)

Linux Programmer's Manual

STRCPY(3)

DESCRIPTION

The **strncpy()** function is similar, except that at most n bytes of src are copied. **Warning:** If there is no null byte among the first n bytes of src, the string placed in dest will not be null-terminated.

If the length of src is less than n, **strncpy()** writes additional null bytes to dest to ensure that a total of n bytes are written.

A simple implementation of **strncpy()** might be:

```
1 char *strncpy(char *dest, const char *src, size_t n) {
2     size_t i;
3     for (i = 0; i < n && src[i] != '\0'; i++)
4         dest[i] = src[i];
5     for ( ; i < n; i++)
6         dest[i] = '\0';
7     return dest;
8 }
```

	0x60	0x61	0x62	0x63	0x64	0x65	0x66
buf	'M'	'o'	'n'	'd'	'a'	'y'	'\0'
	0x58	0x59	0x5a	0x5b			
str	'F'	'r'	'i'	'\0'			

What happens if we call `strncpy(buf, str, 5);`?



Code study: strncpy

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4         dest[i] = src[i];
5     for ( ; i < n; i++)
6         dest[i] = '\0';
7     return dest;
8 }
```

	0x60	0x61	0x62	0x63	0x64	0x65	0x66
buf	'M'	'o'	'n'	'd'	'a'	'y'	'\0'

	0x58	0x59	0x5a	0x5b
str	'F'	'r'	'i'	'\0'

dest	<input type="text"/>
src	<input type="text"/>
n	<input type="text" value="5"/>
i	<input type="text"/>

What happens if we call `strncpy(buf, str, 5);`?

Bonus: Tricky addresses

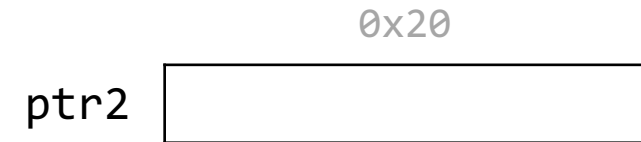
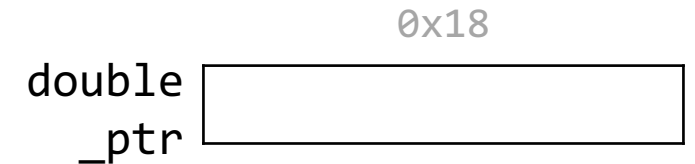
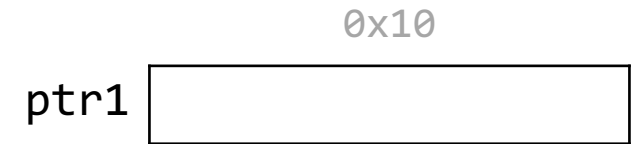
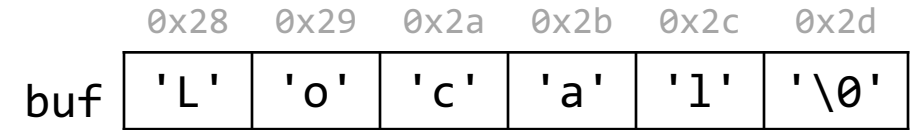
```
1 void tricky_addresses() {
2     char buf[] = "Local";
3     char *ptr1 = buf;
4     char **double_ptr = &ptr1;
5     printf("ptr1's value:      %p\n", ptr1);
6     printf("ptr1's deref      : %c\n", *ptr1);
7     printf("          address:   %p\n", &ptr1);
8     printf("double_ptr value: %p\n", double_ptr);
9     printf("buf's address:      %p\n", &buf);
10
11     char *ptr2 = &buf;
12     printf("ptr2's value:      %s\n", ptr2);
13 }
```

What is stored in each variable?



Bonus: Tricky addresses

```
1 void tricky_addresses() {
2     char buf[] = "Local";
3     char *ptr1 = buf;
4     char **double_ptr = &ptr1;
5     printf("ptr1's value:      %p\n", ptr1);
6     printf("ptr1's deref:      %c\n", *ptr1);
7     printf("          address:   %p\n", &ptr1);
8     printf("double_ptr value: %p\n", double_ptr);
9     printf("buf's address:     %p\n", &buf);
10
11     char *ptr2 = &buf;
12     printf("ptr2's value:      %s\n", ptr2);
13 }
```



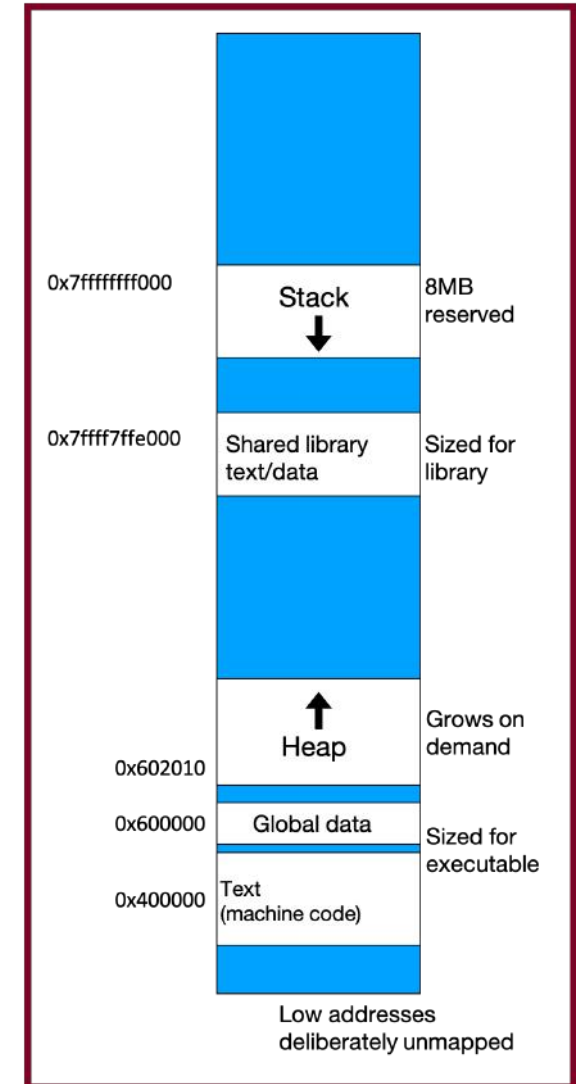
While Line 10 raises a compiler warning, functionally it will still work—because pointers are **addresses**.

Lecture Plan

- Arrays in Memory
- Arrays of Pointers
- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

Memory Layout

- We are going to dive deeper into different areas of memory used by our programs.
- The **stack** is the place where all local variables and parameters live for each function. A function's stack "frame" goes away when the function returns.
- The stack grows **downwards** when a new function is called and shrinks **upwards** when the function is finished.

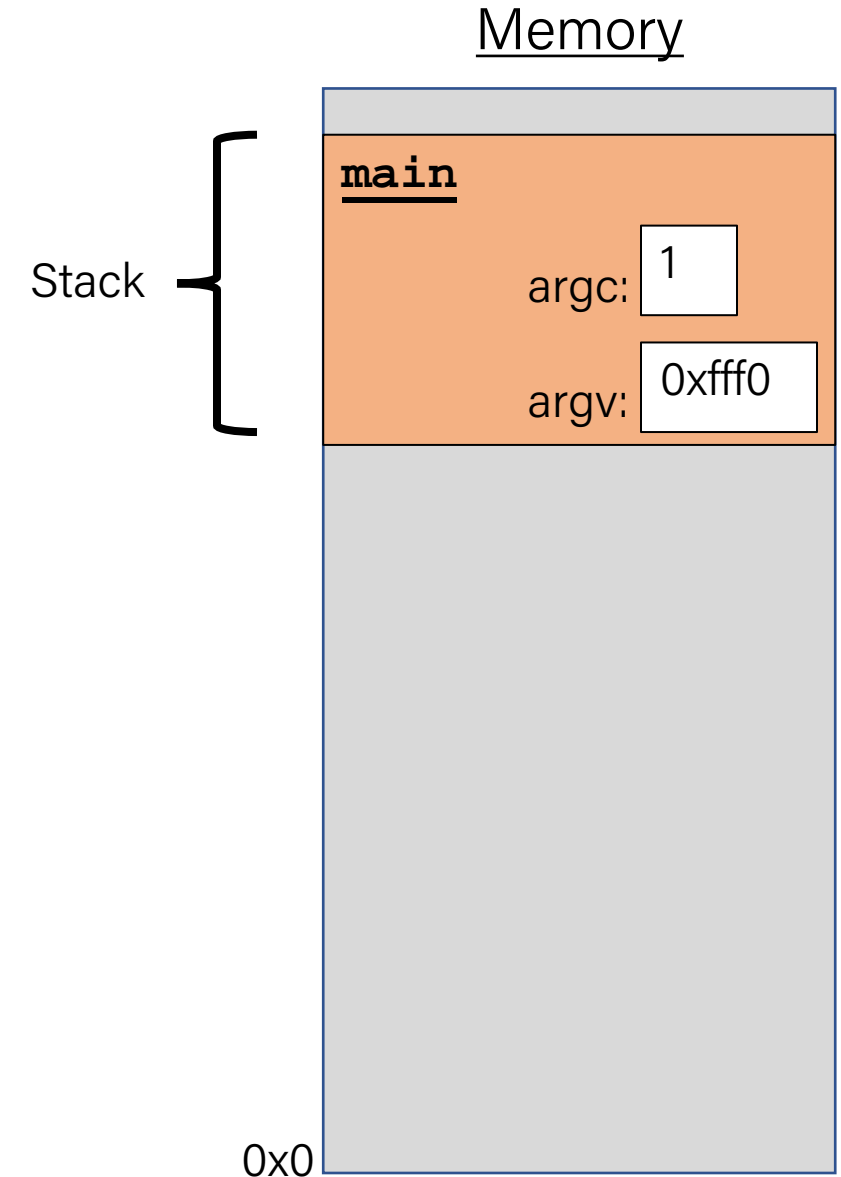


The Stack

```
void func2() {  
    int d = 0;  
}
```

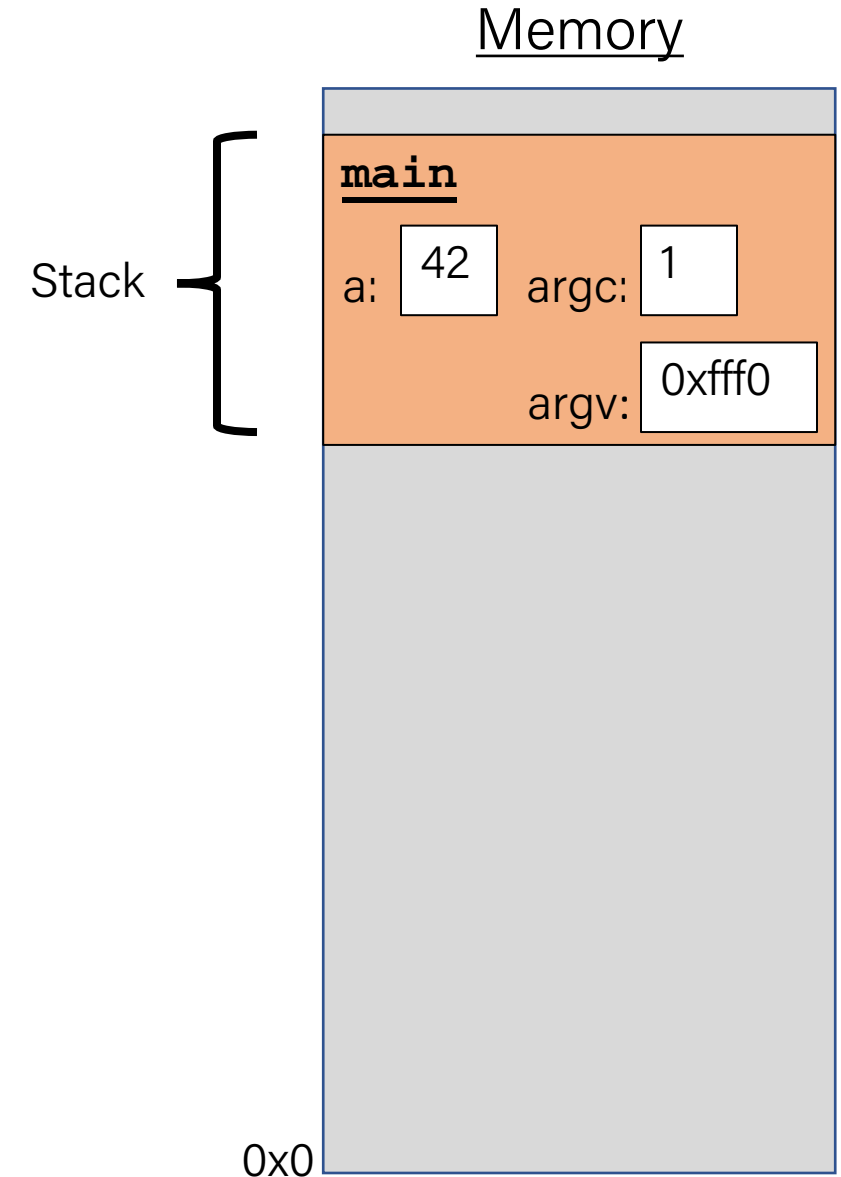
```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```



The Stack

```
void func2() {  
    int d = 0;  
}  
  
void func1() {  
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}  
  
int main(int argc, char *argv[]) {  
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    func1();  
    printf("Done.");  
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```

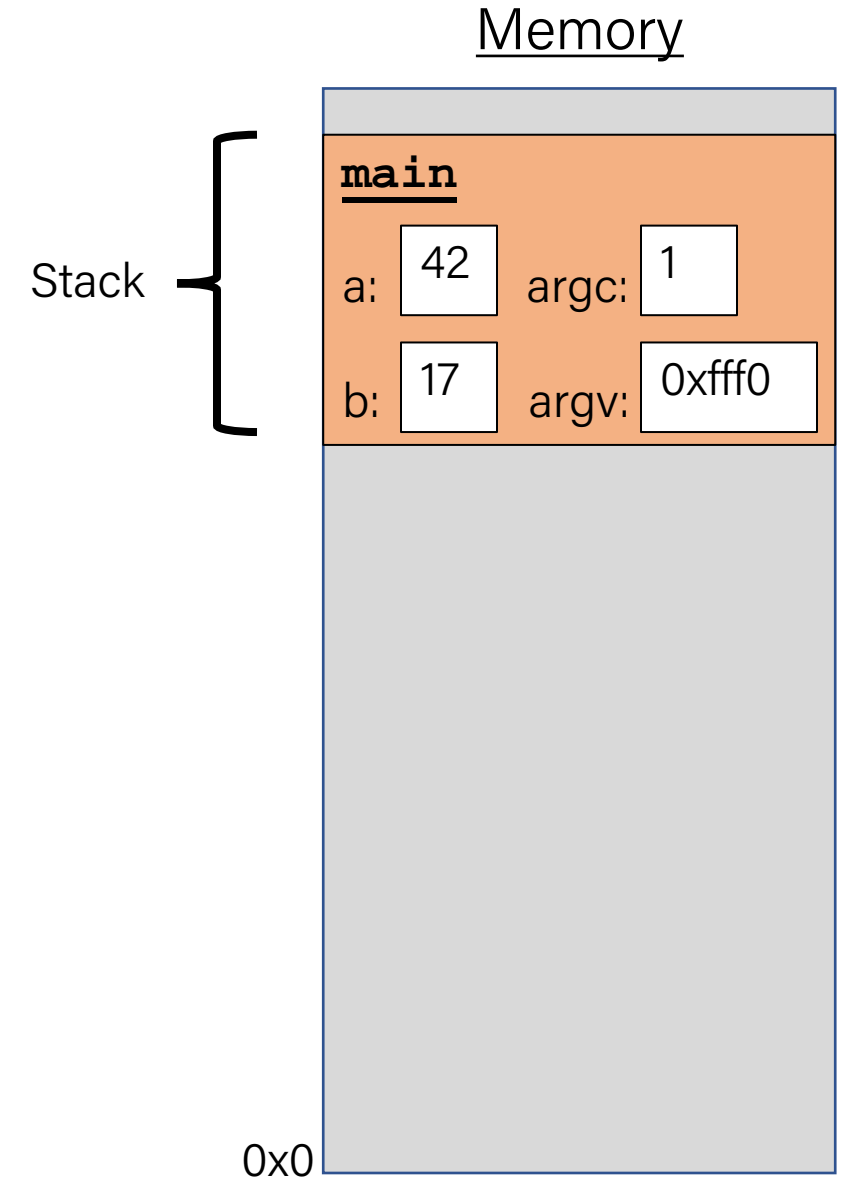


The Stack

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void func2() {  
    int d = 0;  
}
```

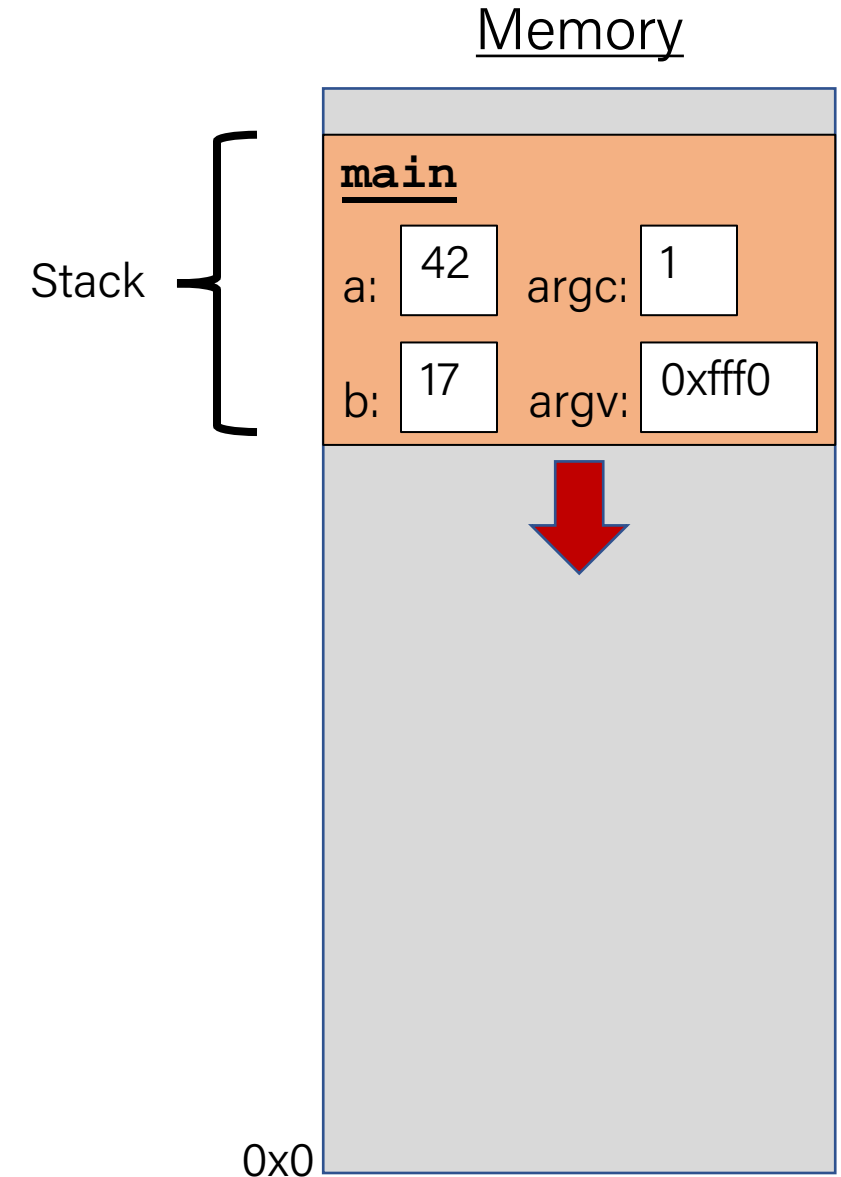
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}
```

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int main(int argc, char *argv[]) {  
    int a = 42;  
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    func1();  
    printf("Done.");  
    return 0;  
}
```



The Stack

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void func2() {  
    int d = 0;  
}  
  
void func1() {  
    int c = 99;  
    func2();  
}  
  
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

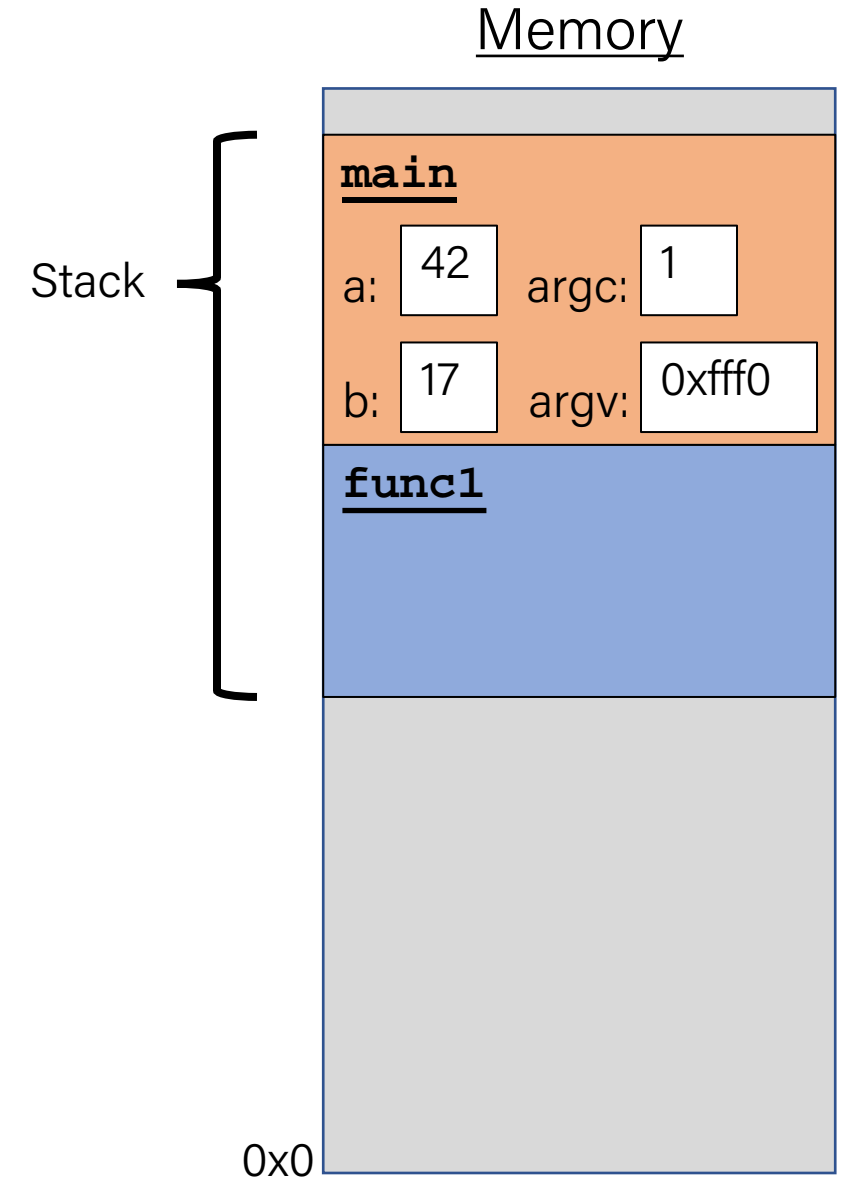


The Stack

```
void func2() {  
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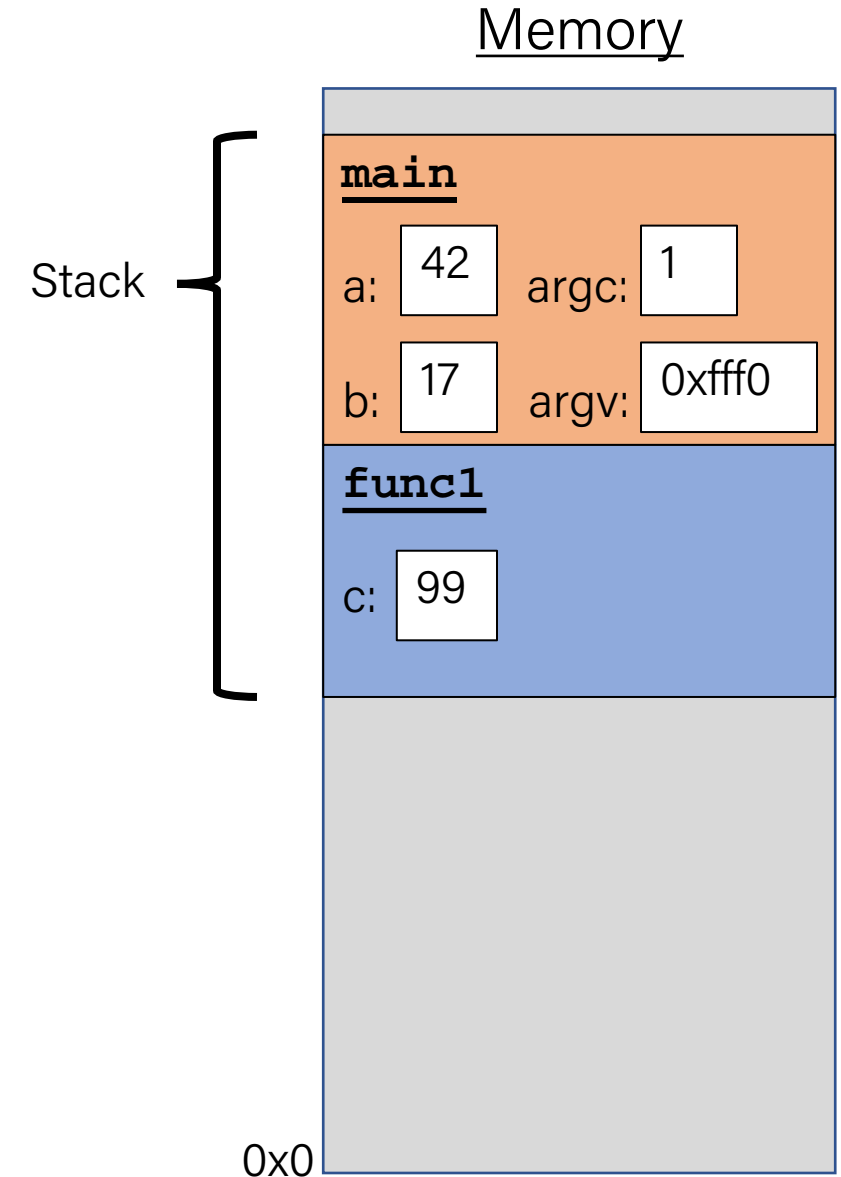
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The Stack

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void func2() {  
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    return 0;  
}
```

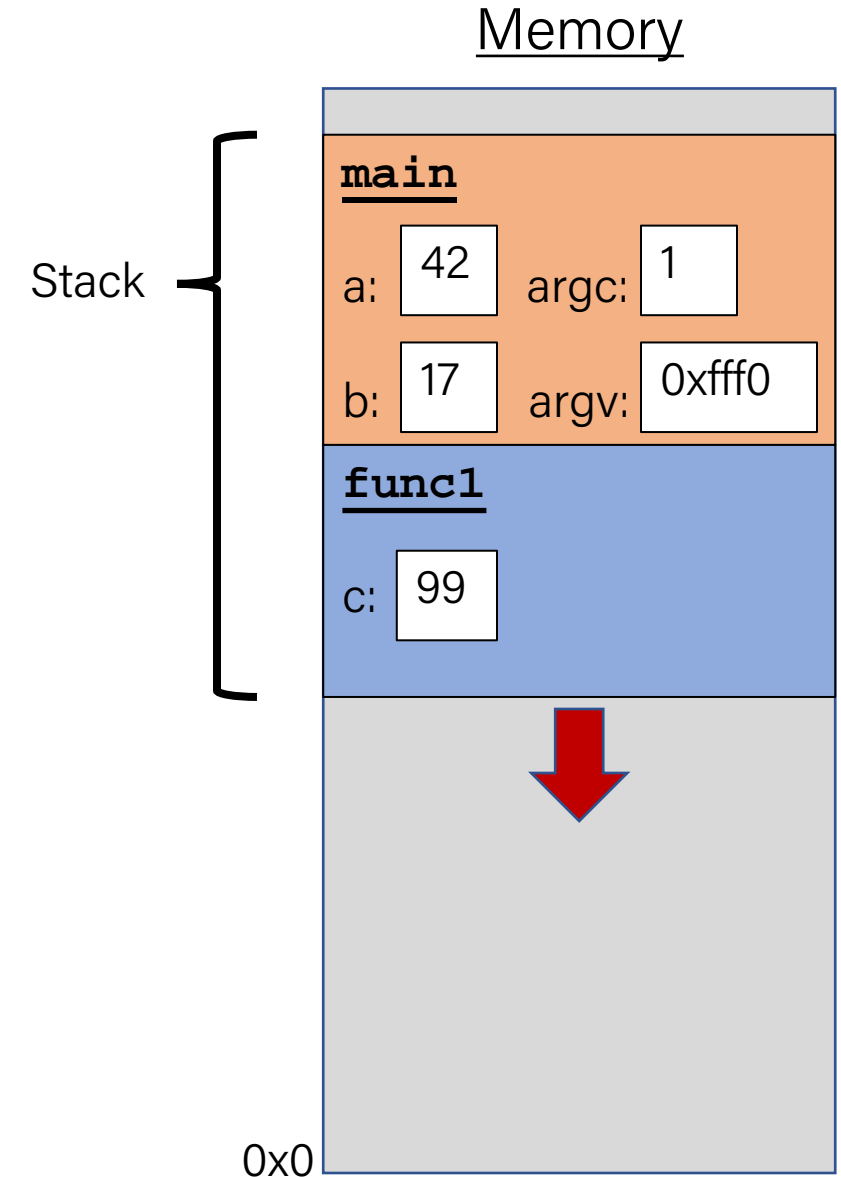


The Stack

```
void func2() {  
    int d = 0;  
}
```

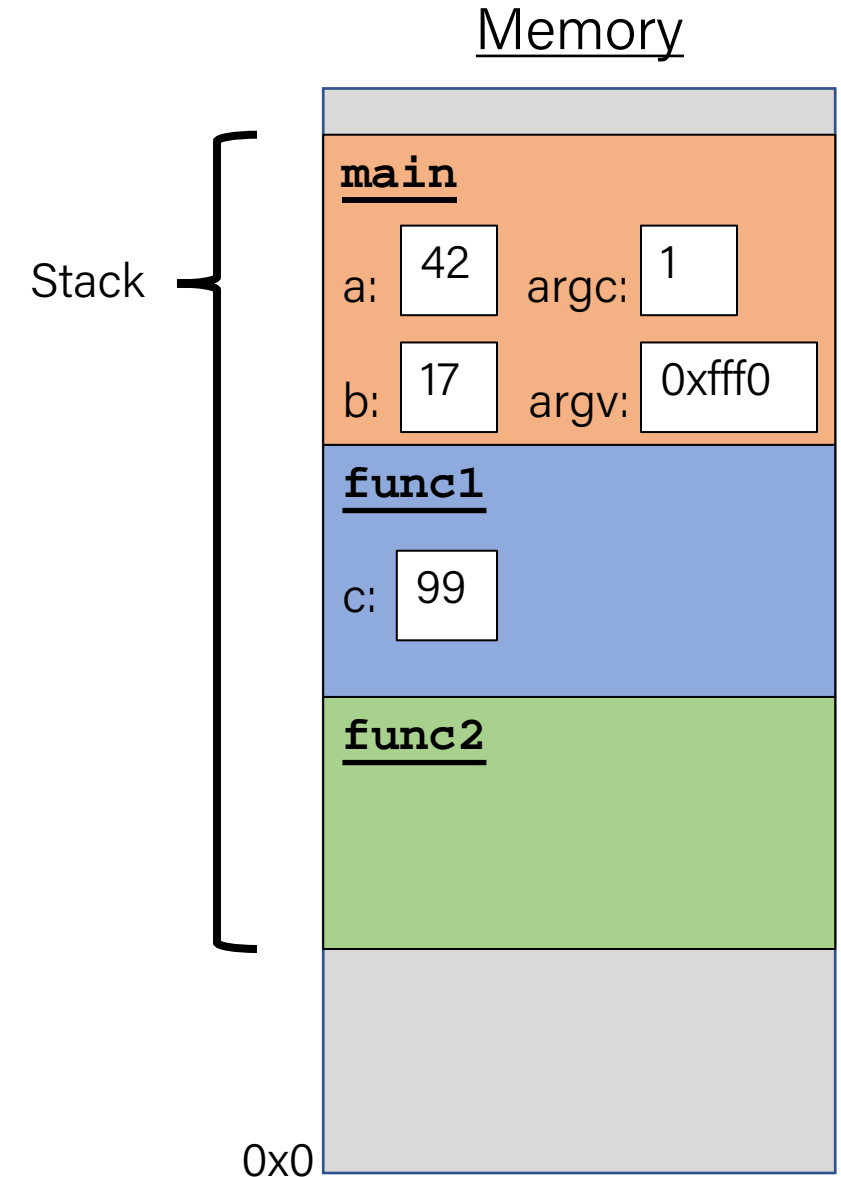
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The Stack

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    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

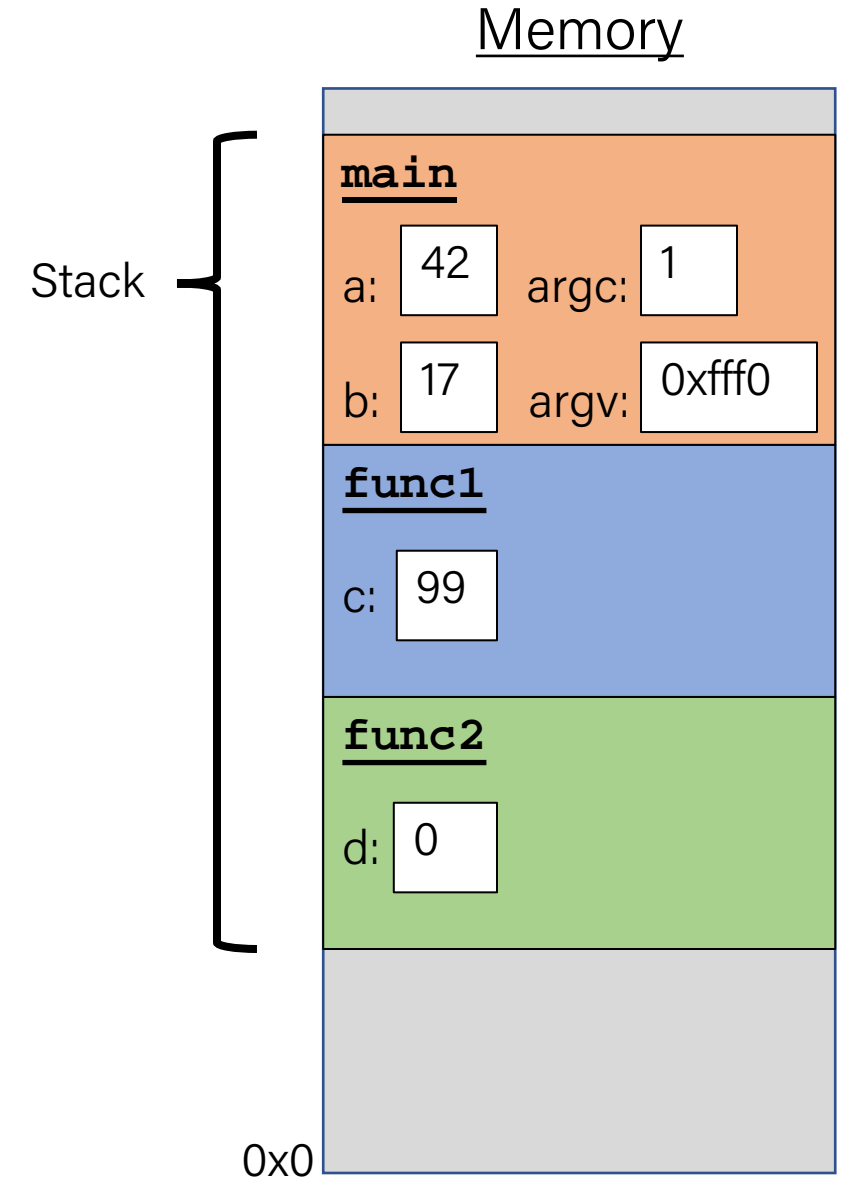


The Stack

```
void func2() {  
    int d = 0;  
}
```

```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

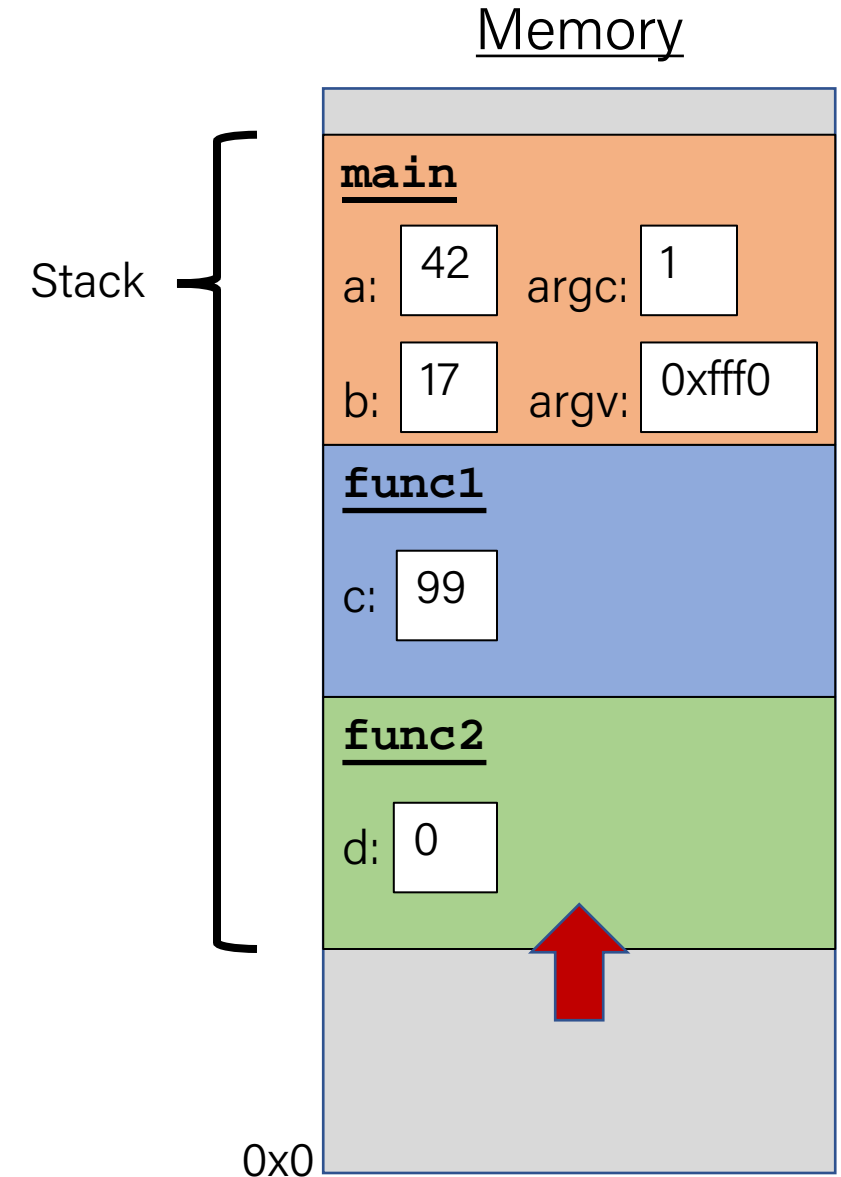


The Stack

```
void func2() {  
    int d = 0;  
}
```

```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

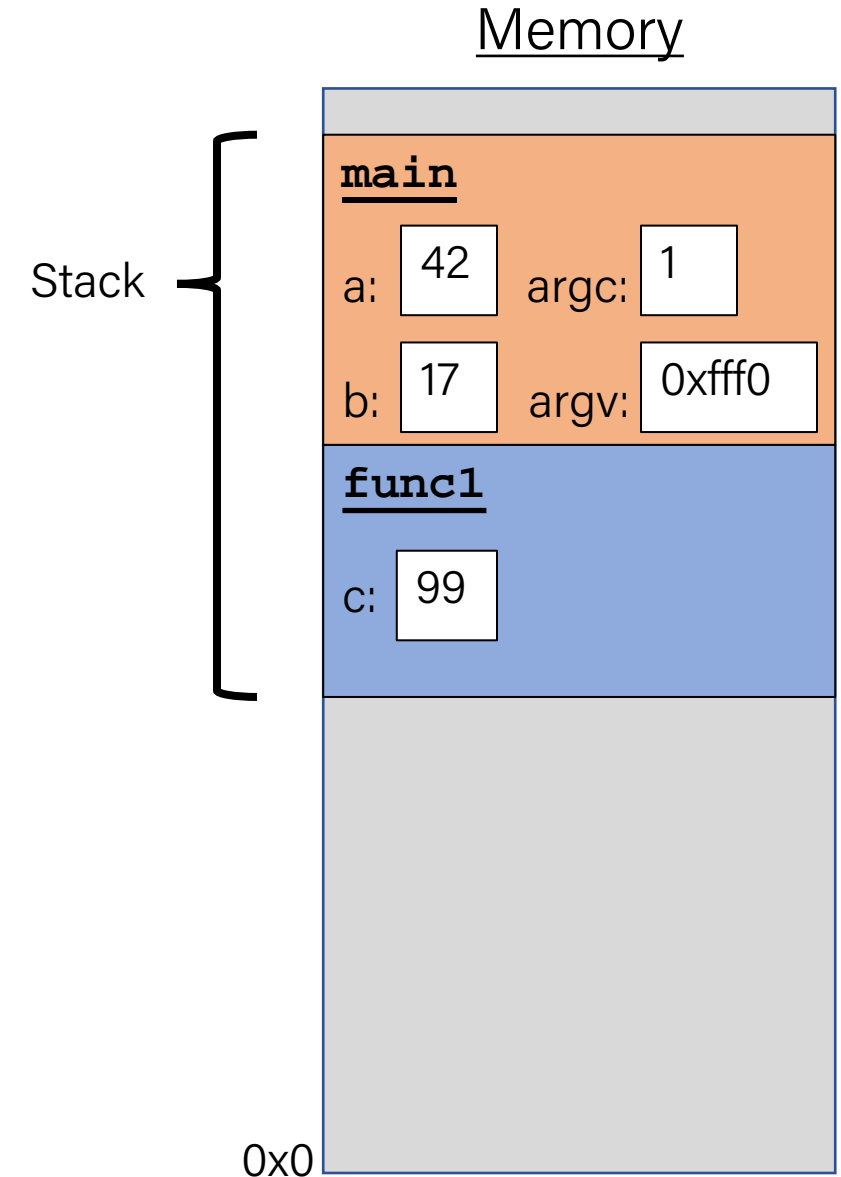


The Stack

```
void func2() {  
    int d = 0;  
}
```

```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

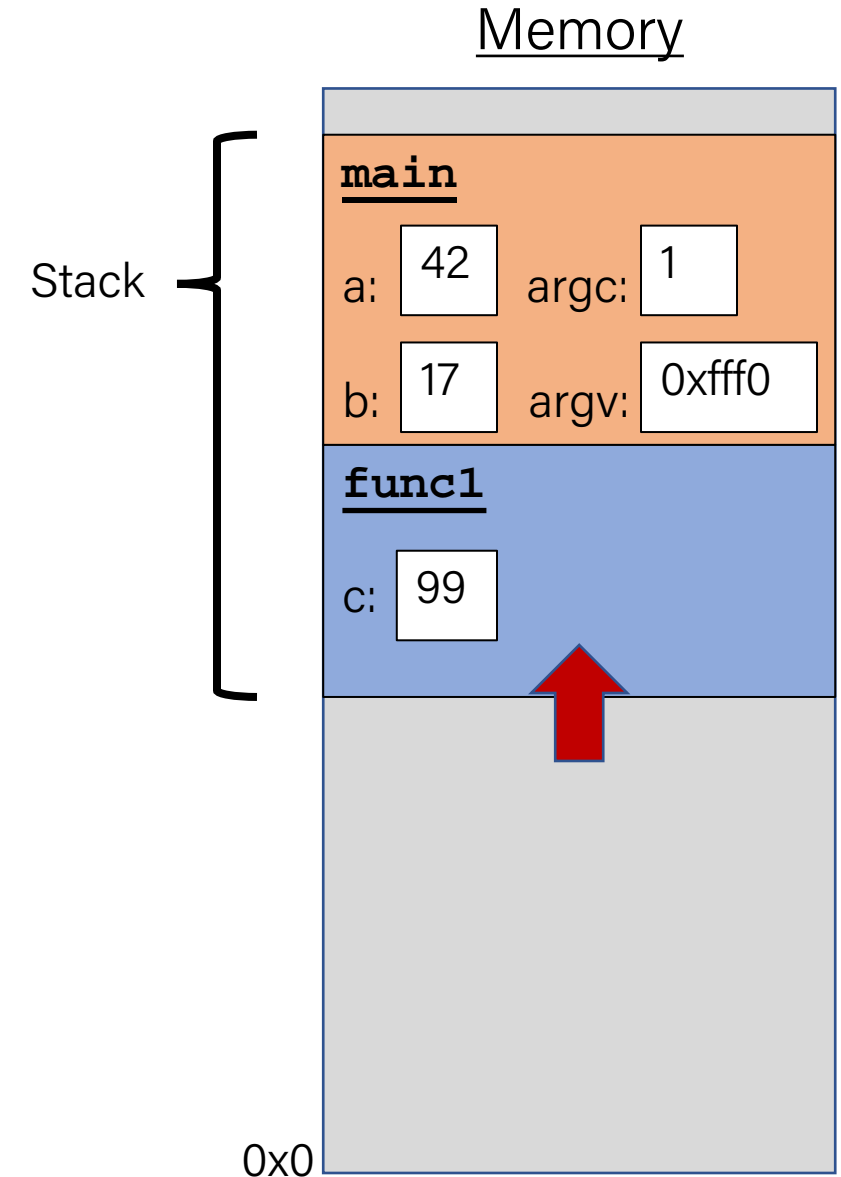


The Stack

```
void func2() {  
    int d = 0;  
}
```

```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

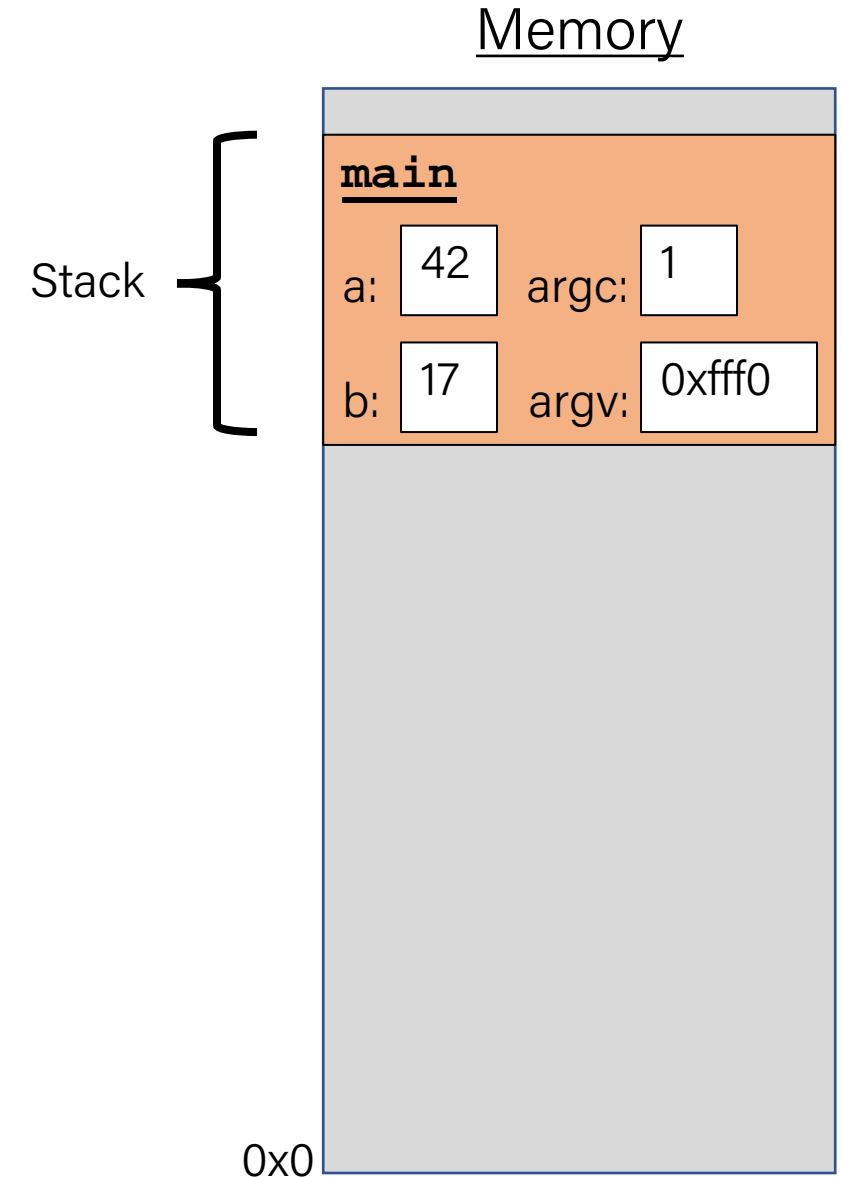


The Stack

```
void func2() {  
    int d = 0;  
}
```

```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

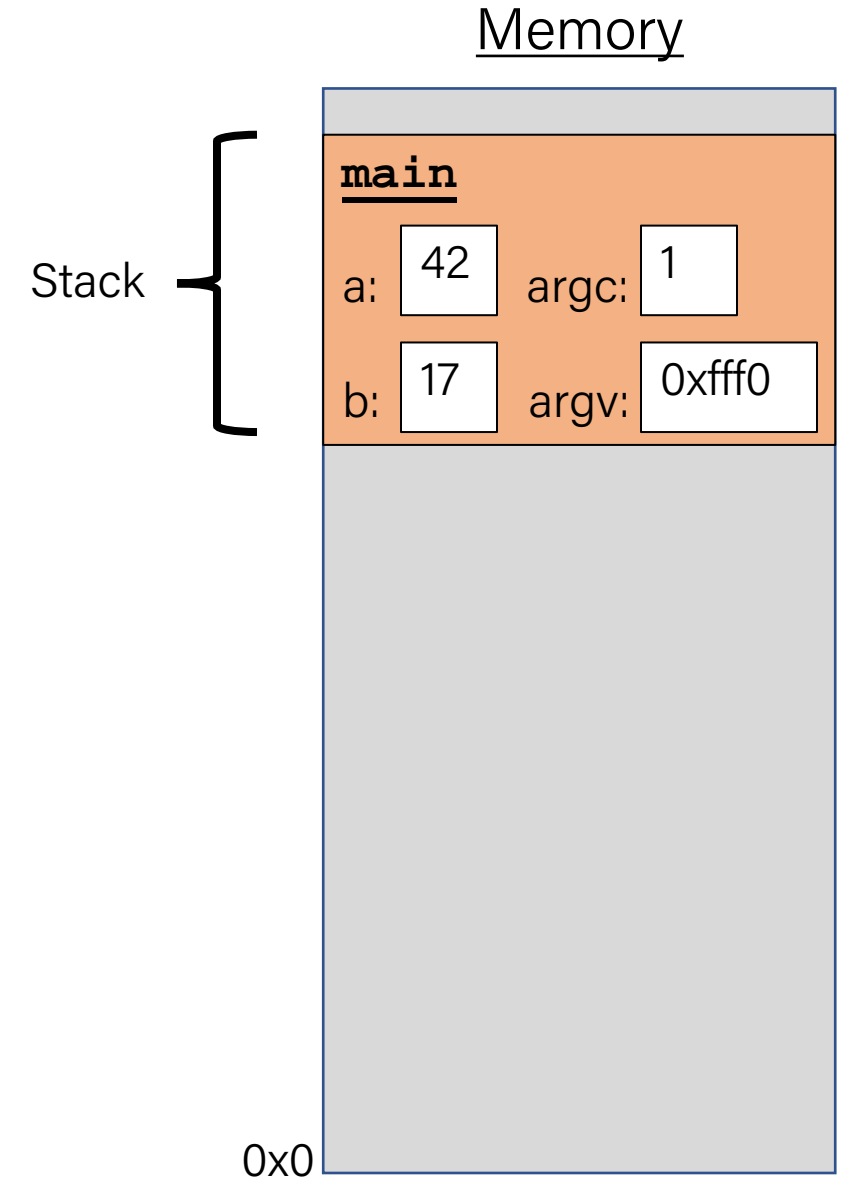


The Stack

```
void func2() {  
    int d = 0;  
}
```

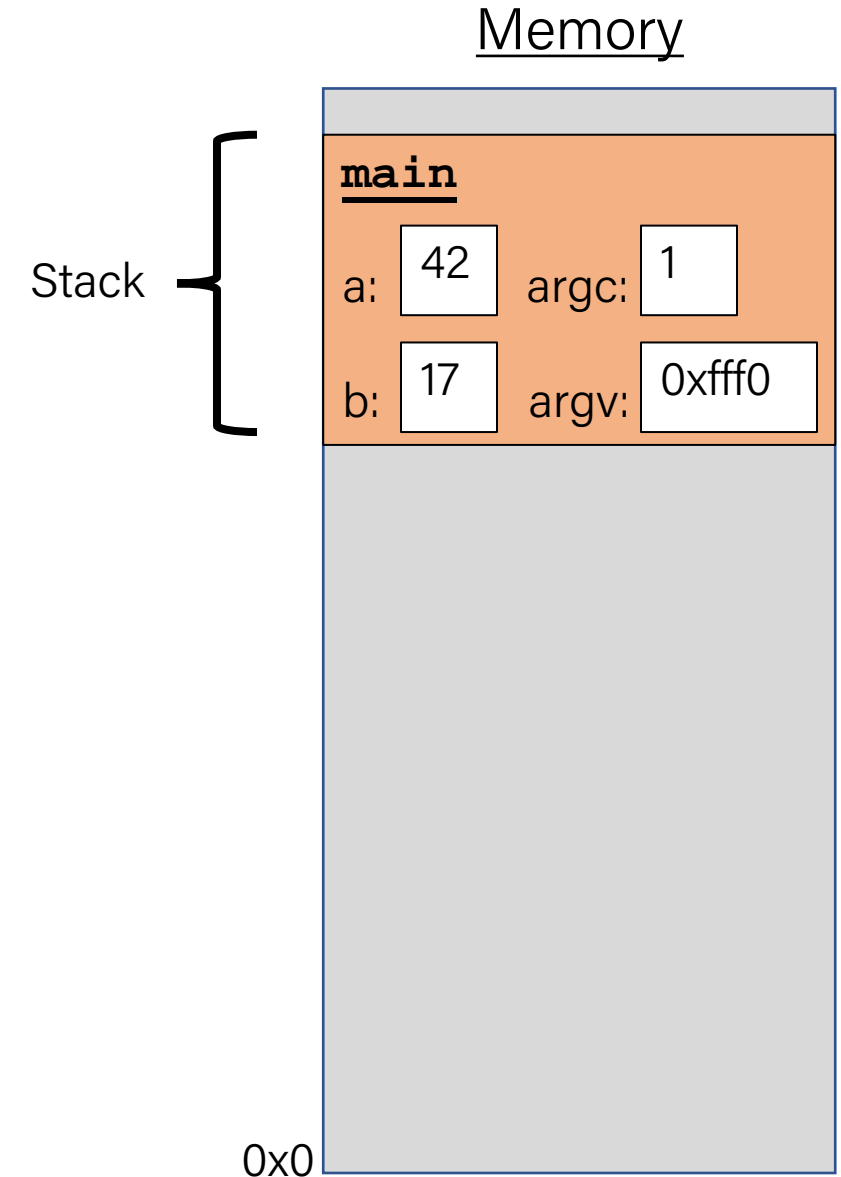
```
void func1() {  
    int c = 99;  
    func2();  
}
```

```
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```



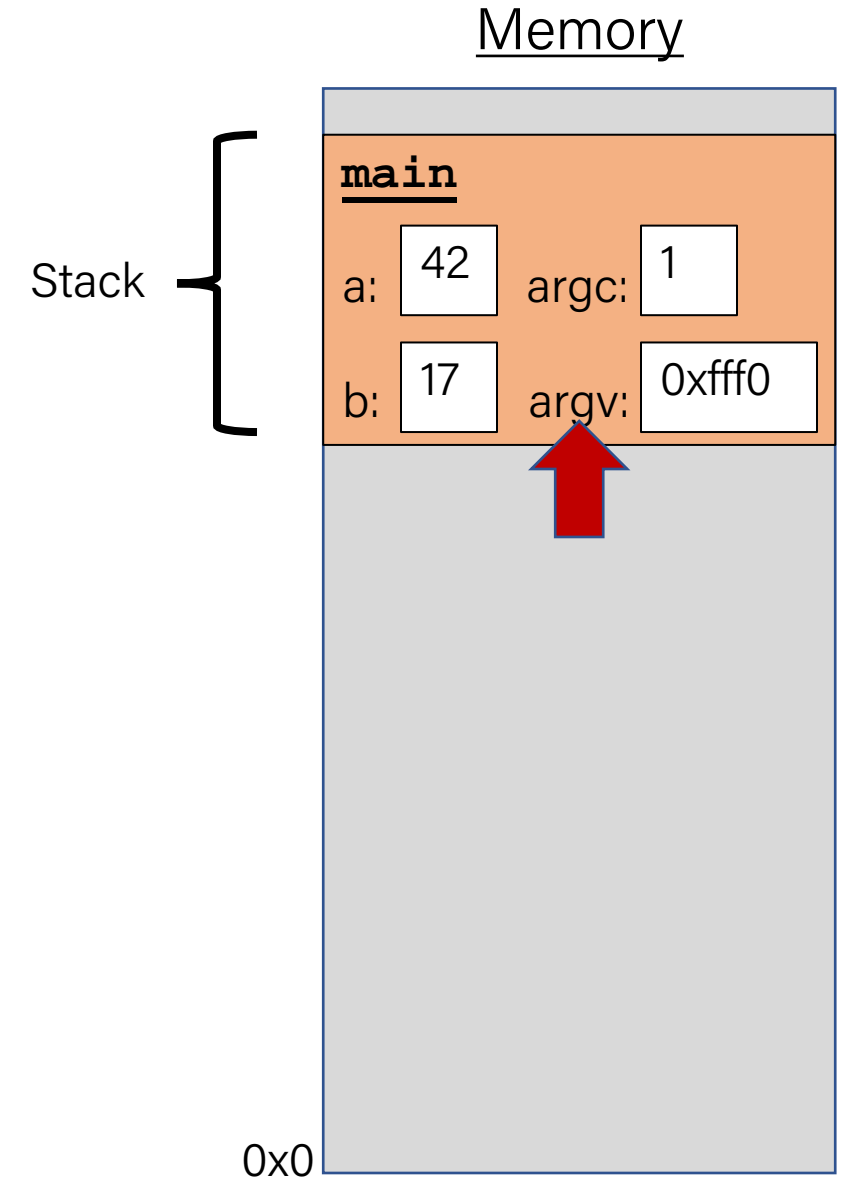
The Stack

```
void func2() {  
    int d = 0;  
}  
  
void func1() {  
    int c = 99;  
    func2();  
}  
  
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```



The Stack

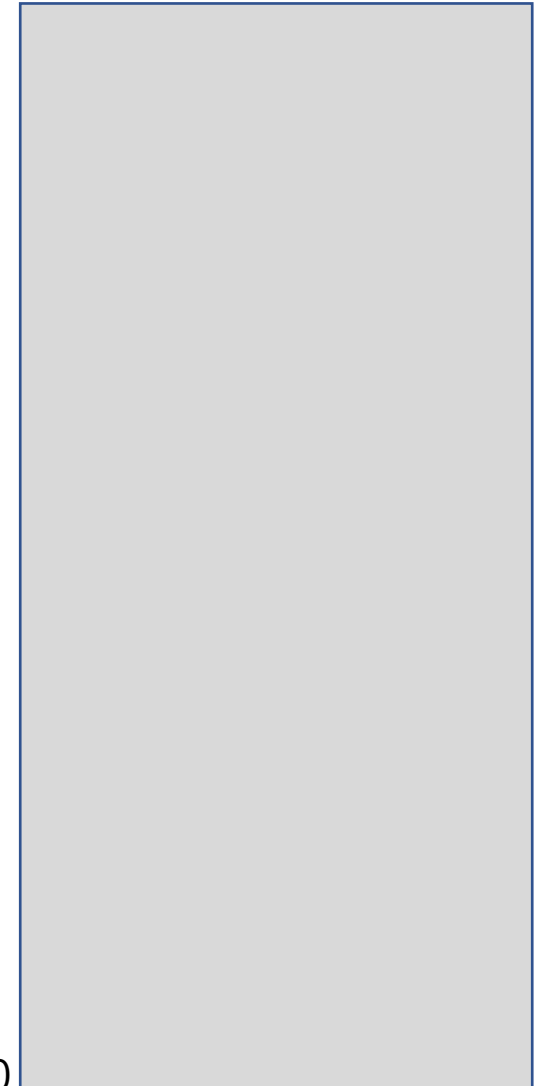
```
void func2() {  
    int d = 0;  
}  
  
void func1() {  
    int c = 99;  
    func2();  
}  
  
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```



The Stack

```
void func2() {  
    int d = 0;  
}  
  
void func1() {  
    int c = 99;  
    func2();  
}  
  
int main(int argc, char *argv[]) {  
    int a = 42;  
    int b = 17;  
    func1();  
    printf("Done.");  
    return 0;  
}
```

Memory



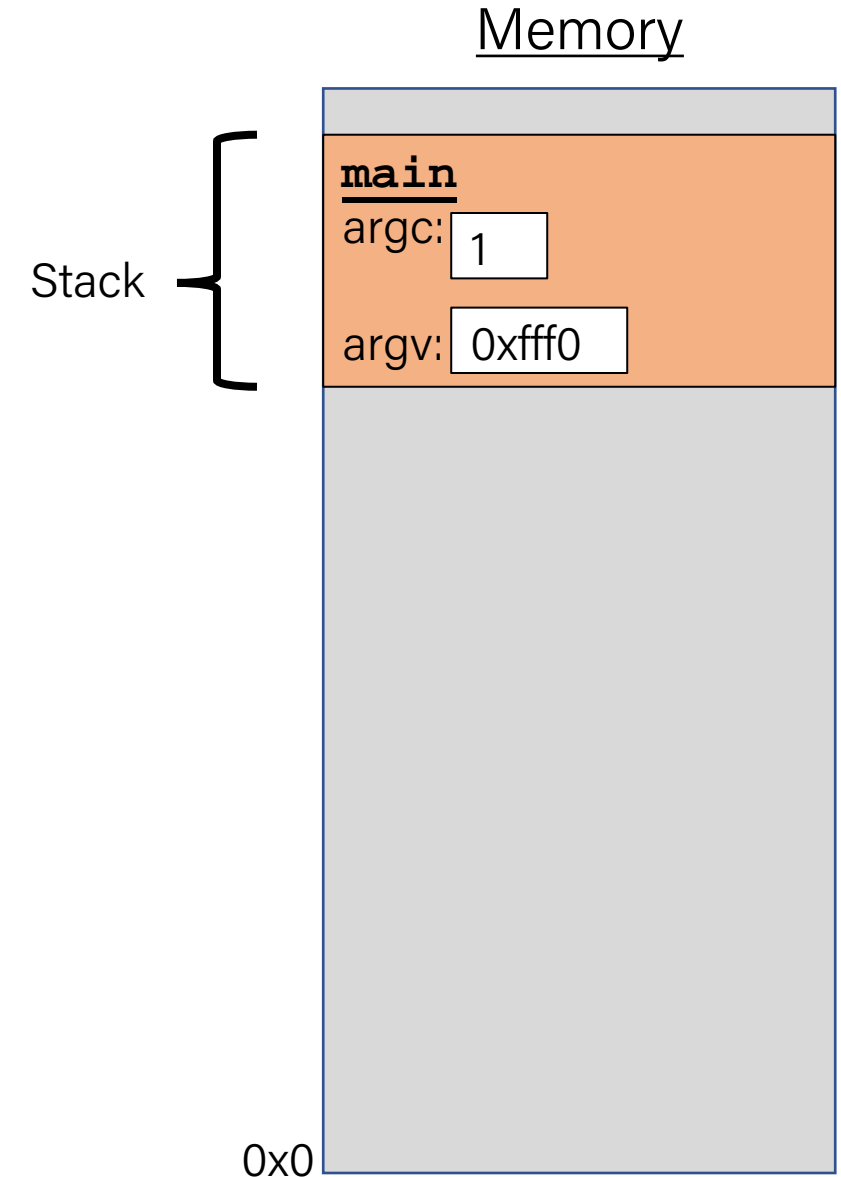
0x0

The Stack

- Each function **call** has its own *stack frame* for its own copy of variables.

```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}
```

```
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```

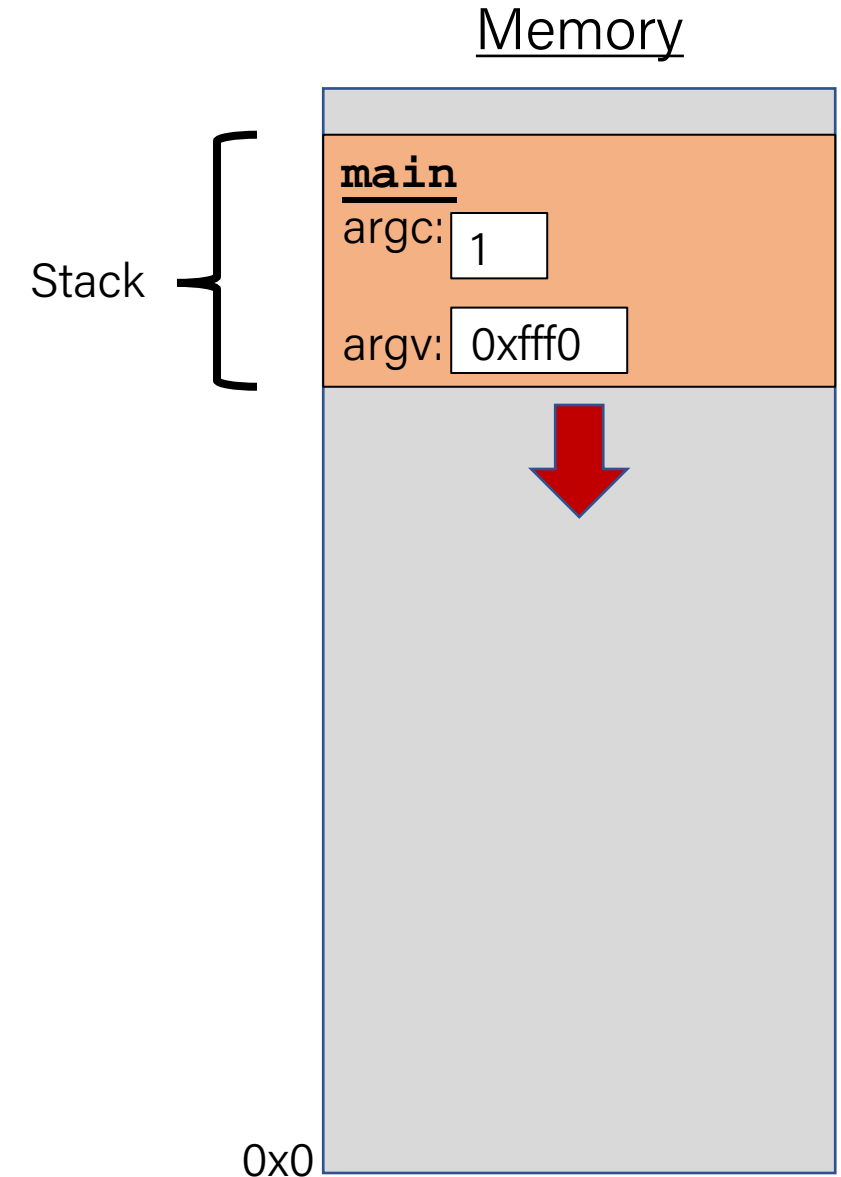


The Stack

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```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}
```

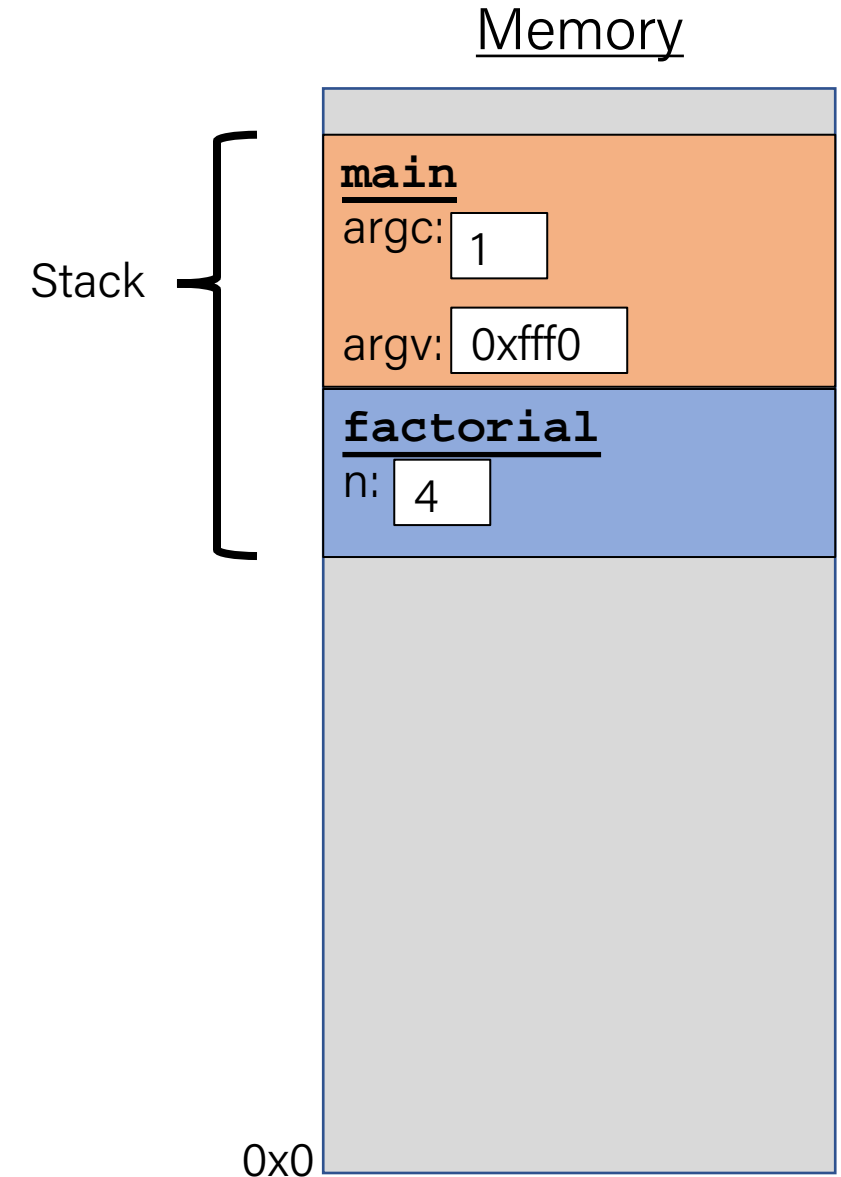
```
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

- Each function **call** has its own *stack frame* for its own copy of variables.

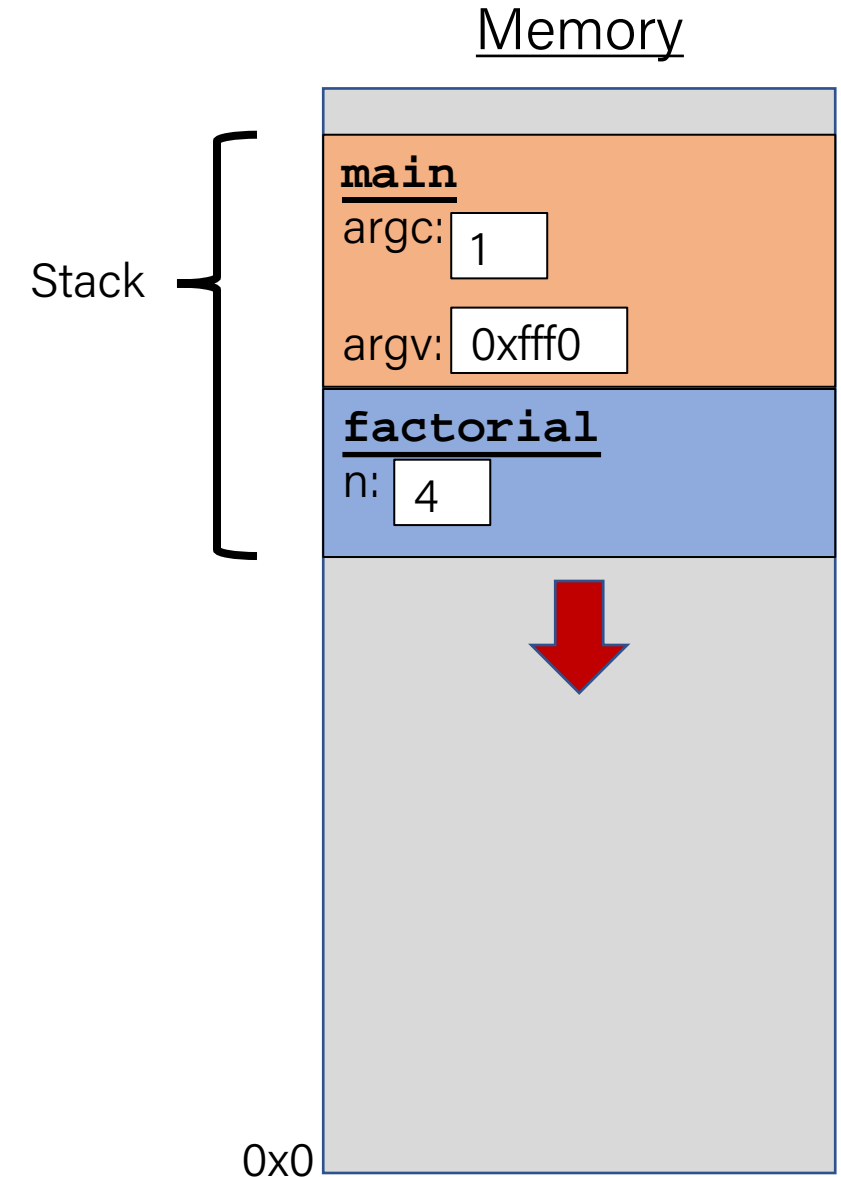
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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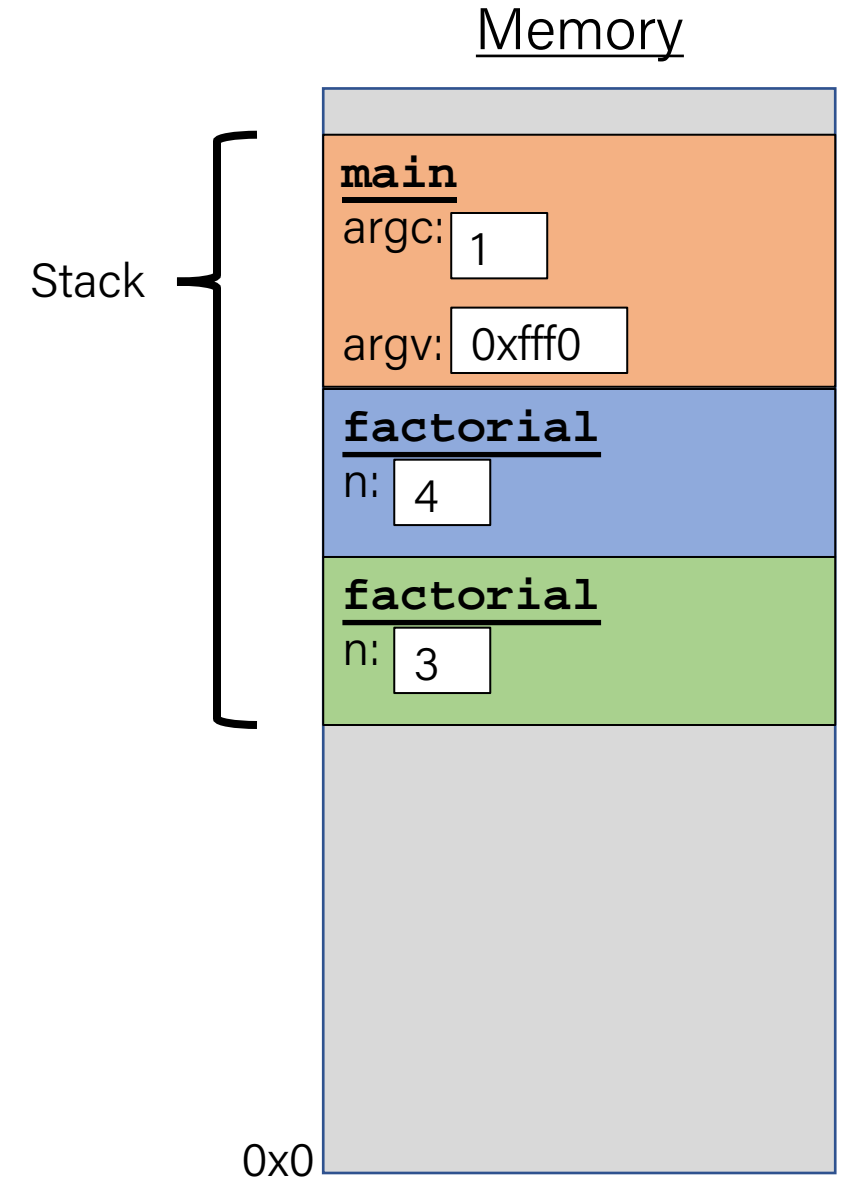
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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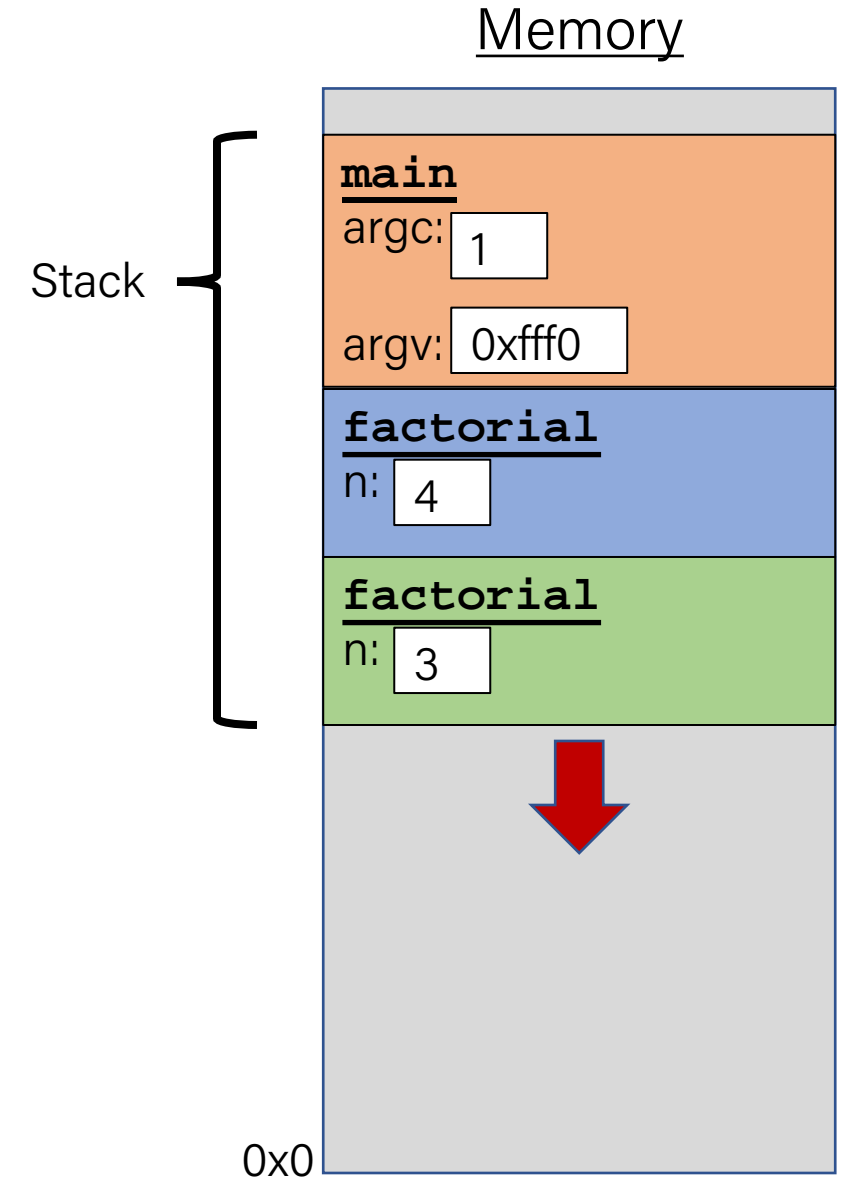
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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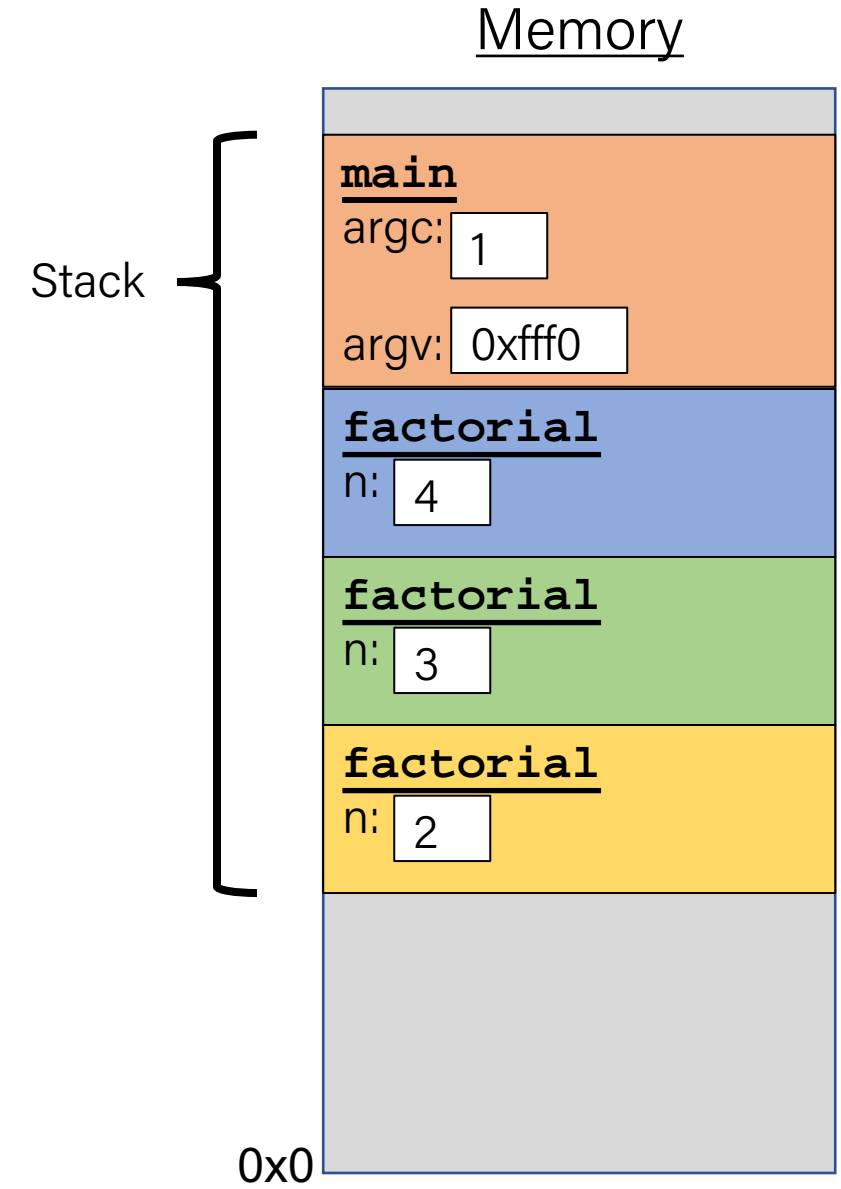
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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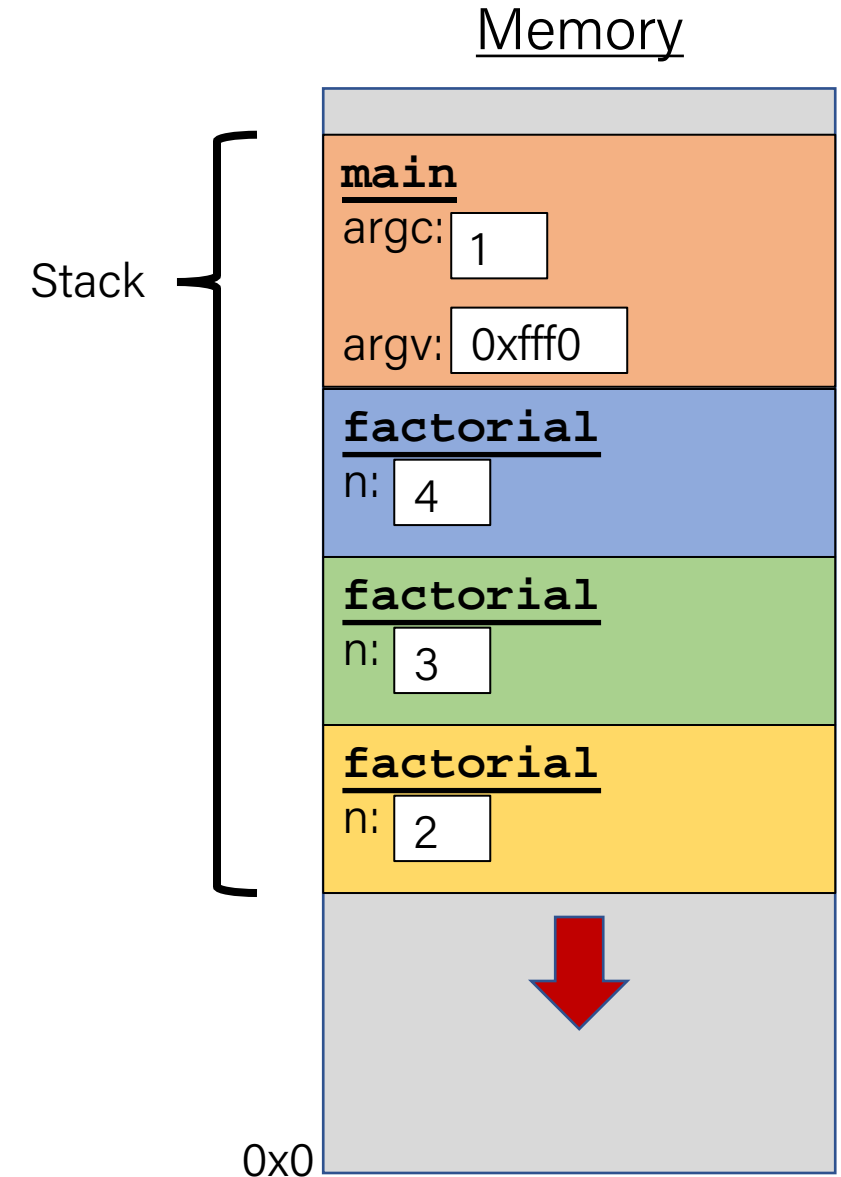
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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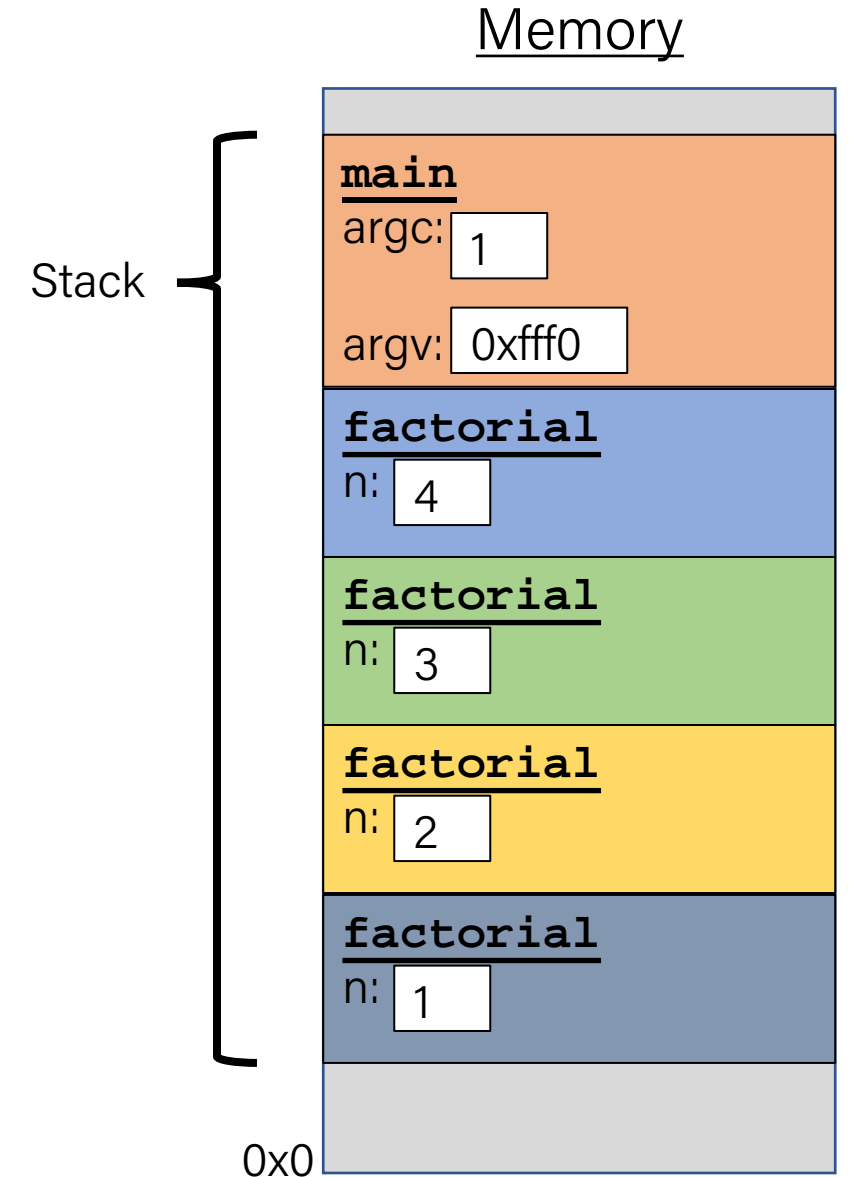
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
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```



The Stack

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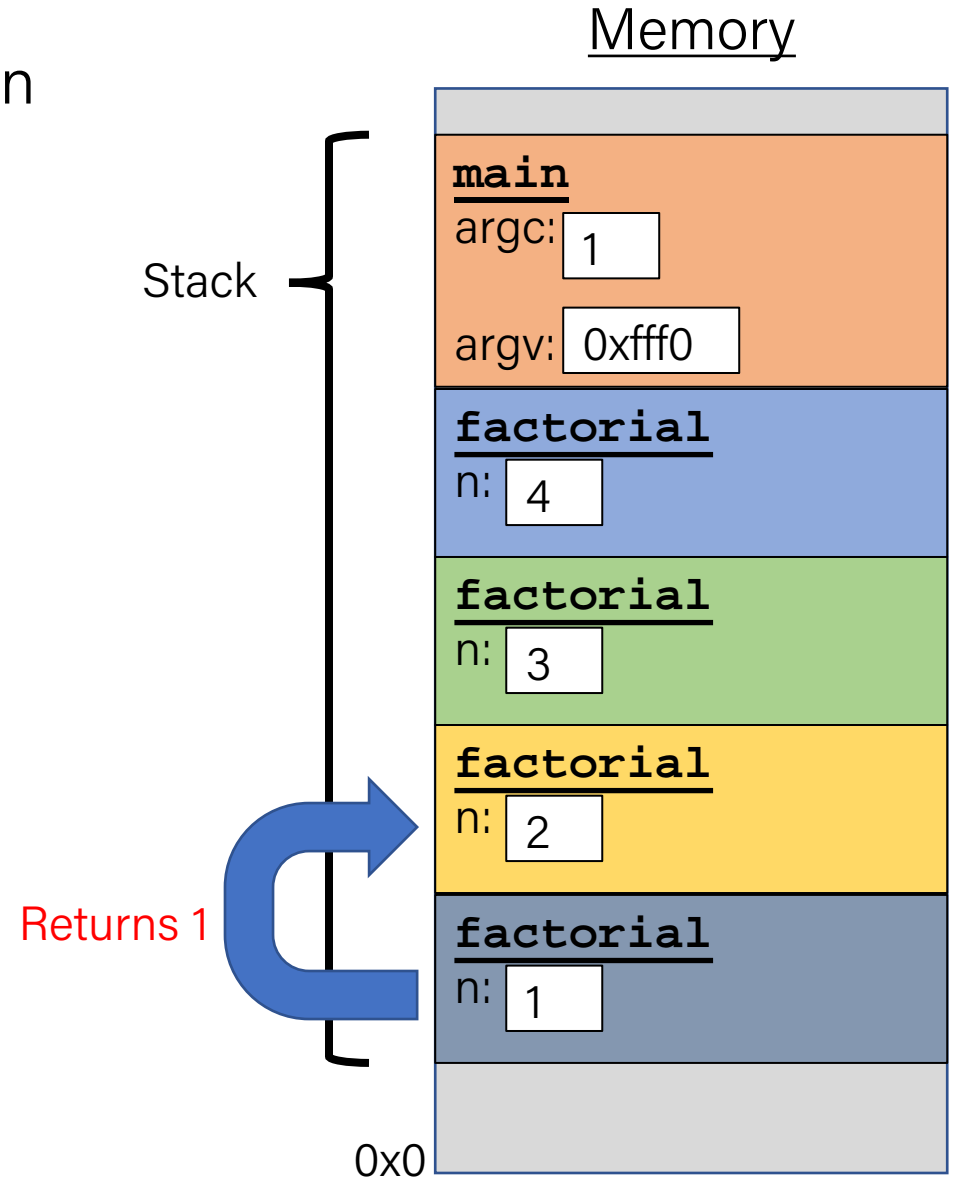
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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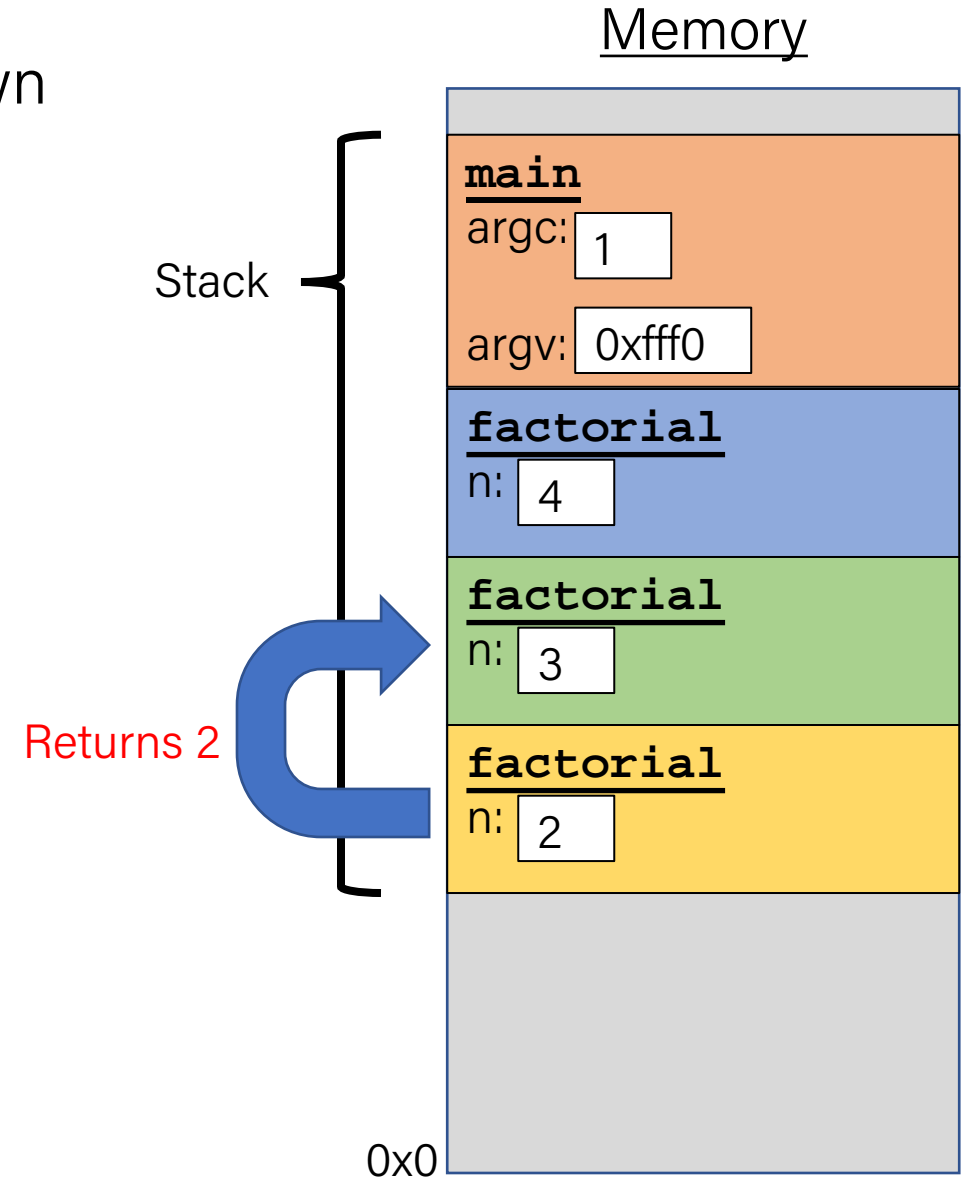
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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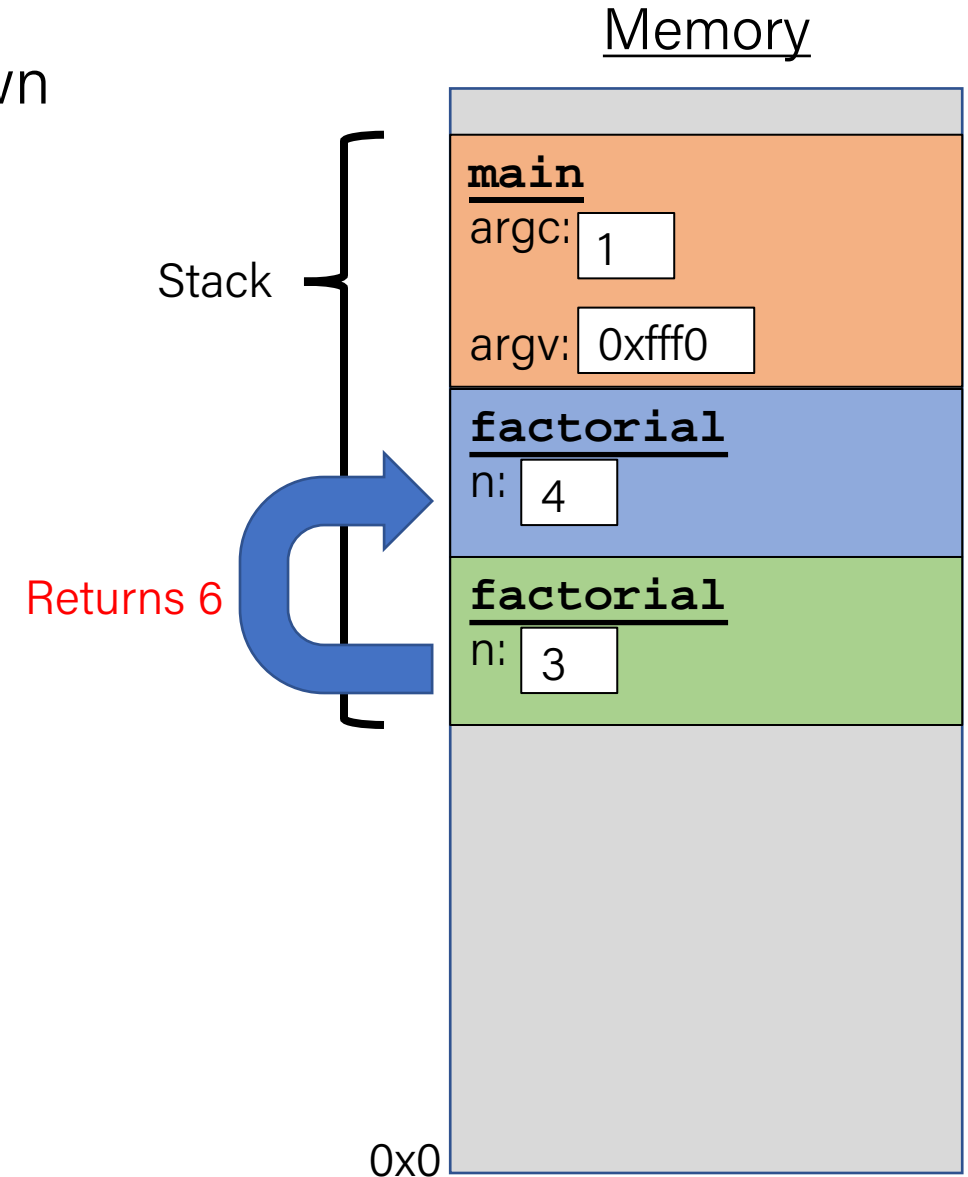
```
int factorial(int n) {  
    if (n == 1) {  
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    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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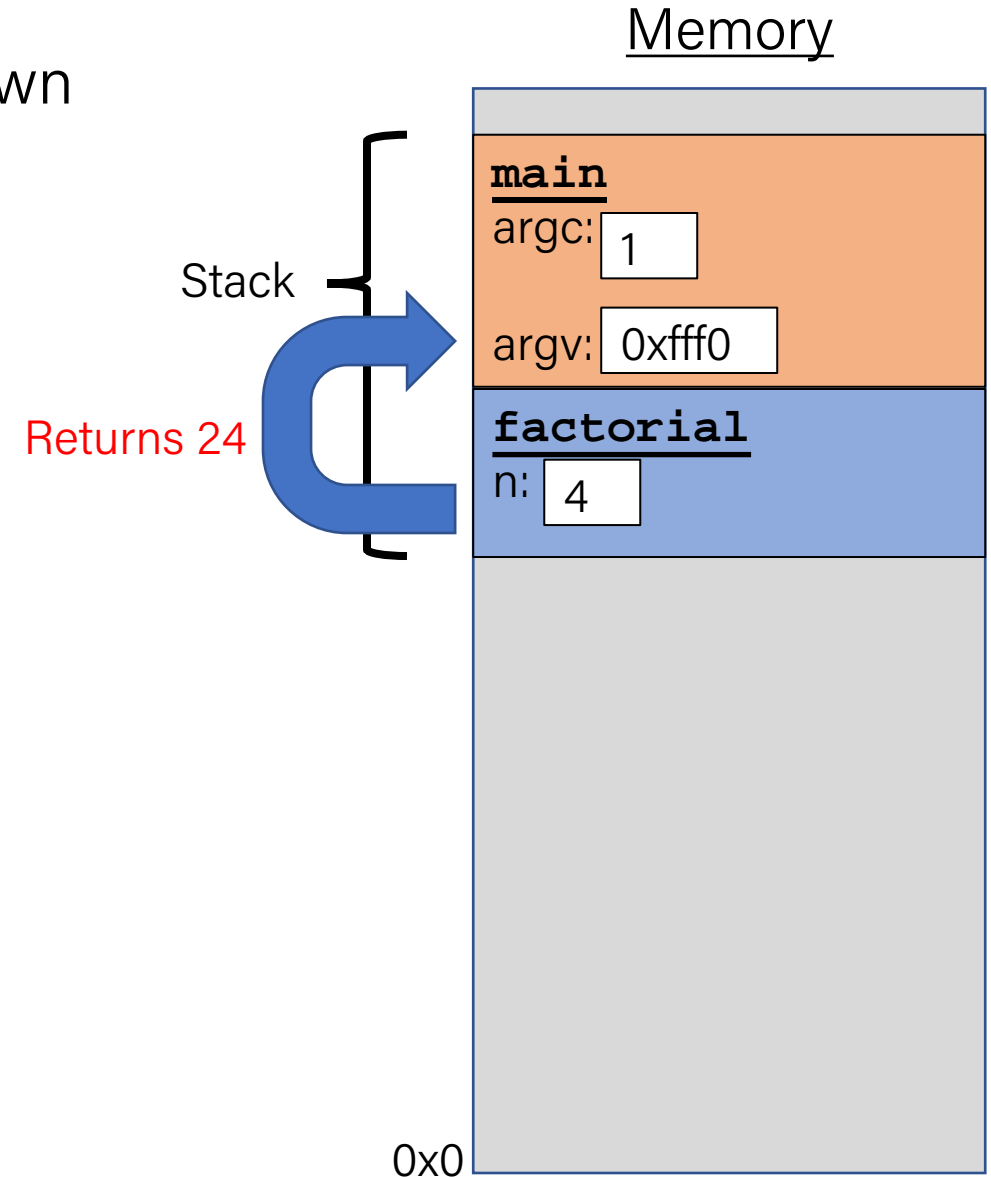
```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



The Stack

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```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}  
  
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```

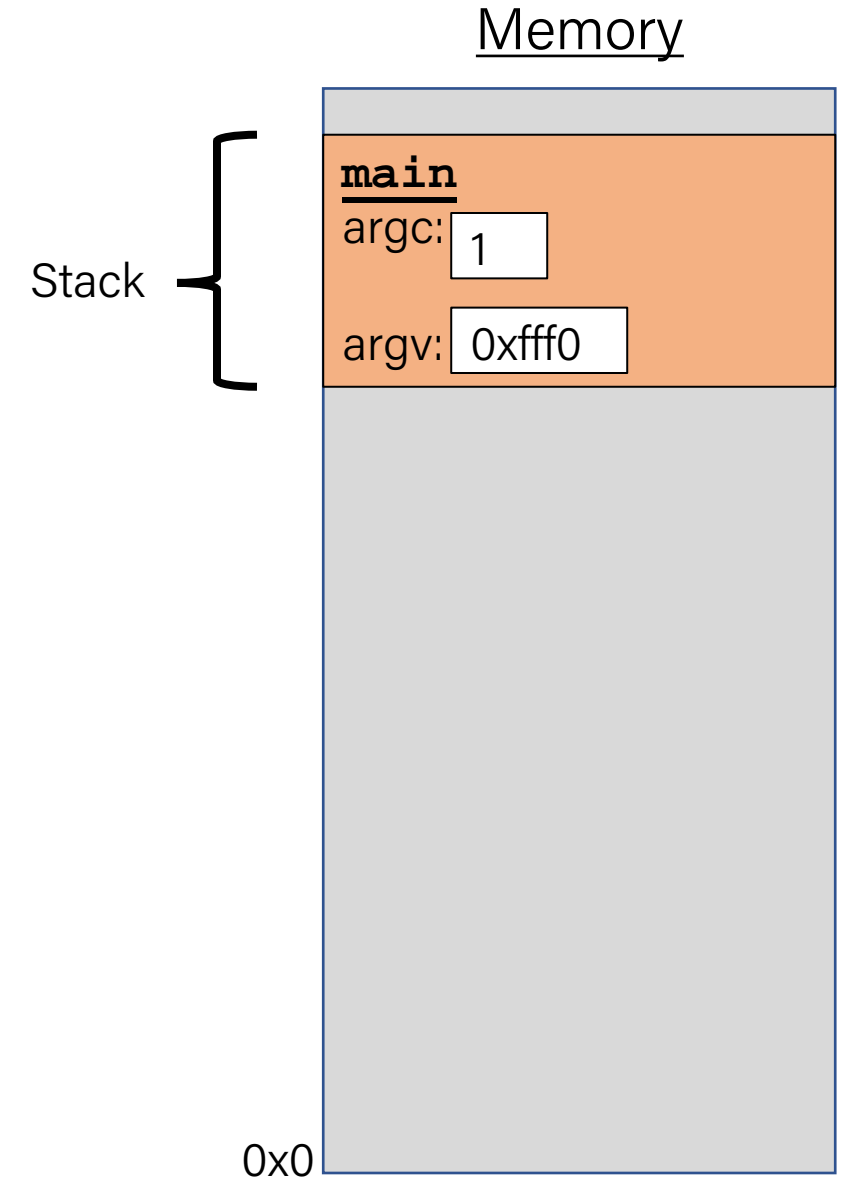


The Stack

- Each function **call** has its own *stack frame* for its own copy of variables.

```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}
```

```
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```

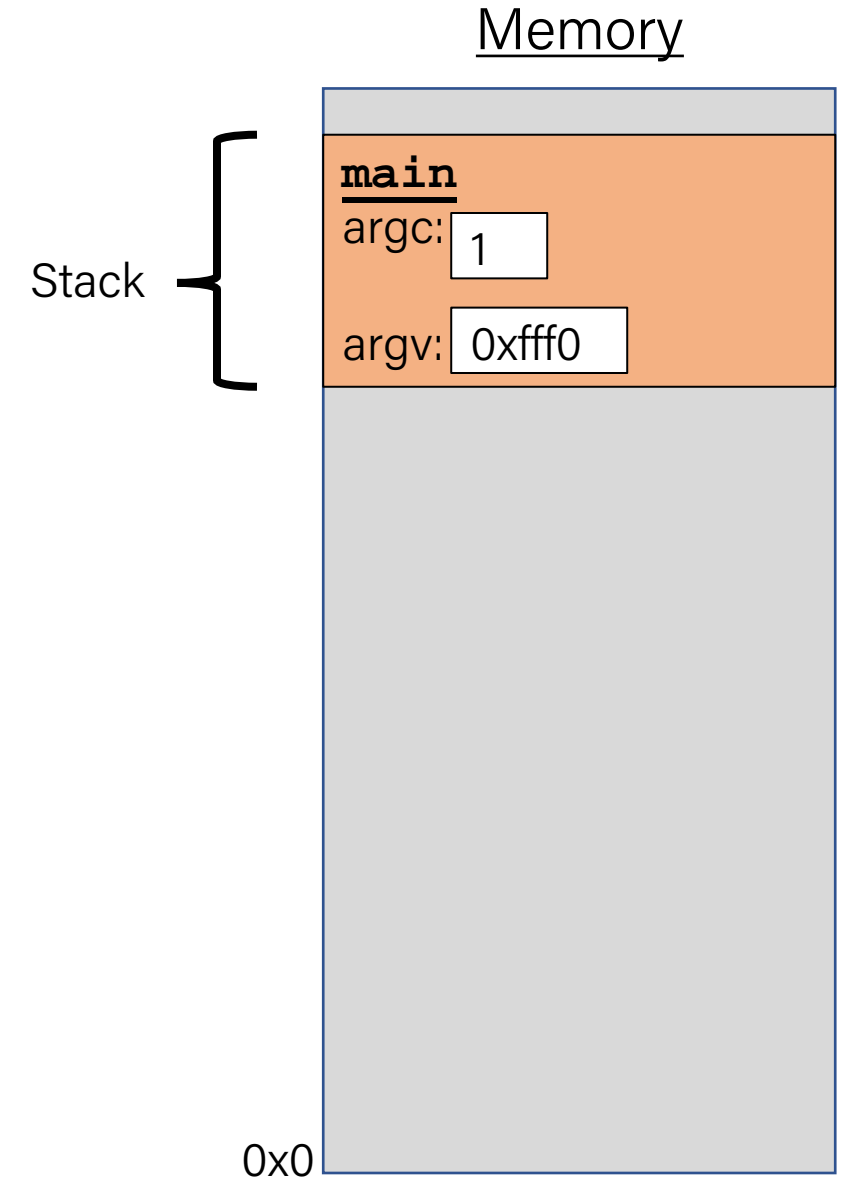


The Stack

- Each function **call** has its own *stack frame* for its own copy of variables.

```
int factorial(int n) {  
    if (n == 1) {  
        return 1;  
    } else {  
        return n * factorial(n - 1);  
    }  
}
```

```
int main(int argc, char *argv[]) {  
    printf("%d", factorial(4));  
    return 0;  
}
```



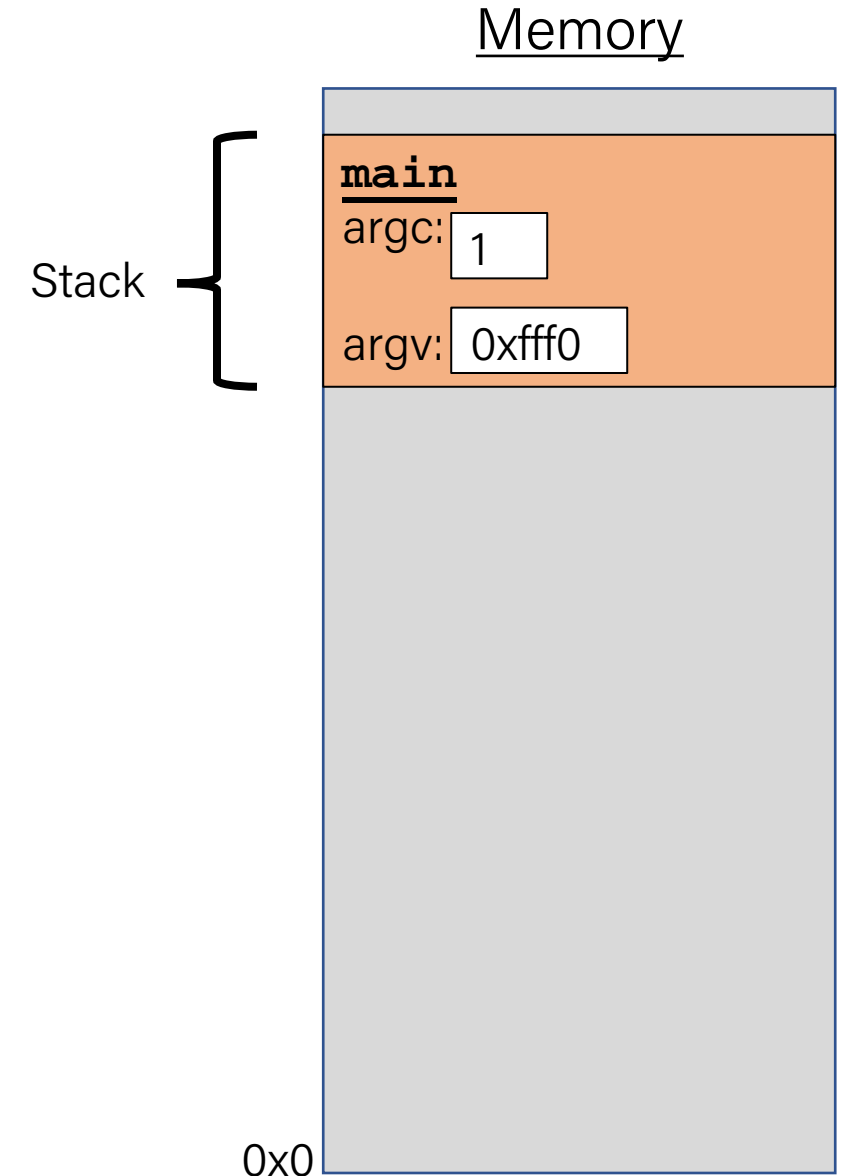
The Stack

- The stack behaves like a...well...stack! A new function call **pushes** on a new frame. A completed function call **pops** off the most recent frame.
- *Interesting fact:* C does not clear out memory when a function's frame is removed. Instead, it just marks that memory as usable for the next function call. This is more efficient!
- A *stack overflow* is when you use up all stack memory. E.g. a recursive call with too many function calls.
- What are the limitations of the stack?

The Stack

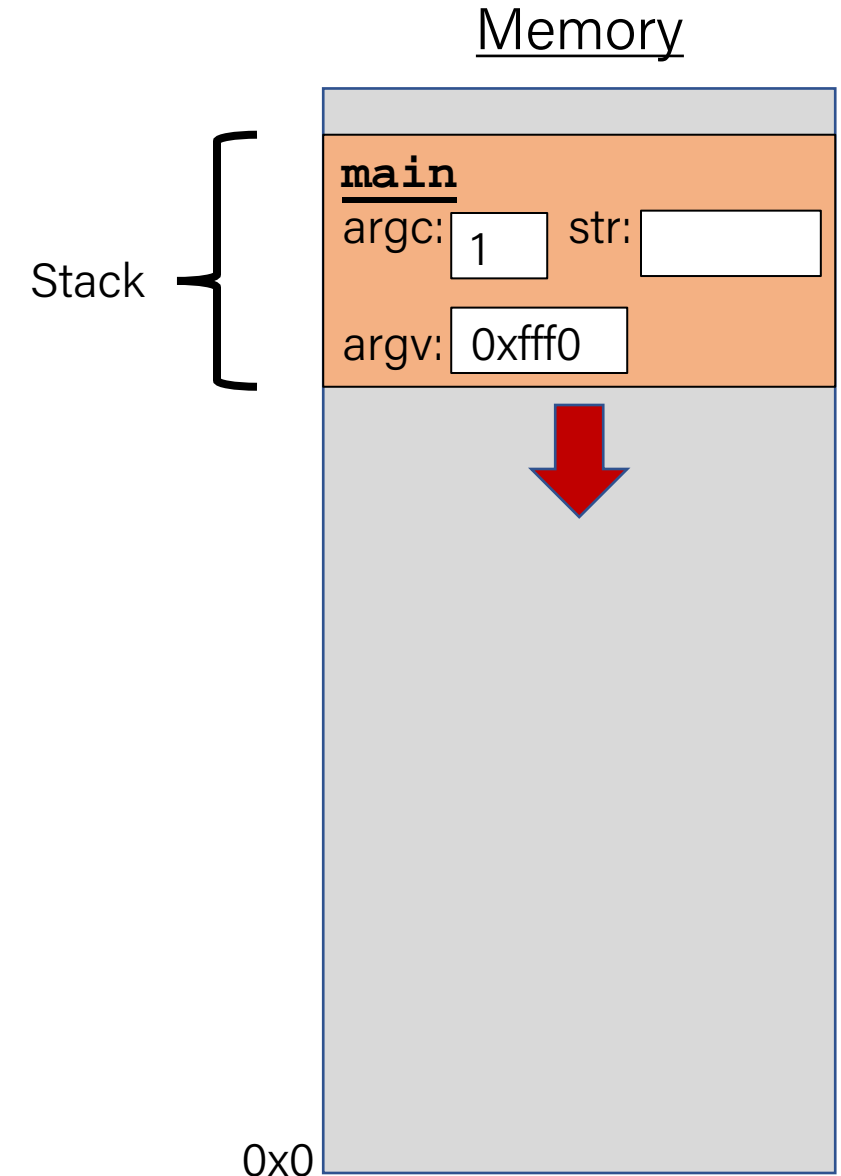
```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



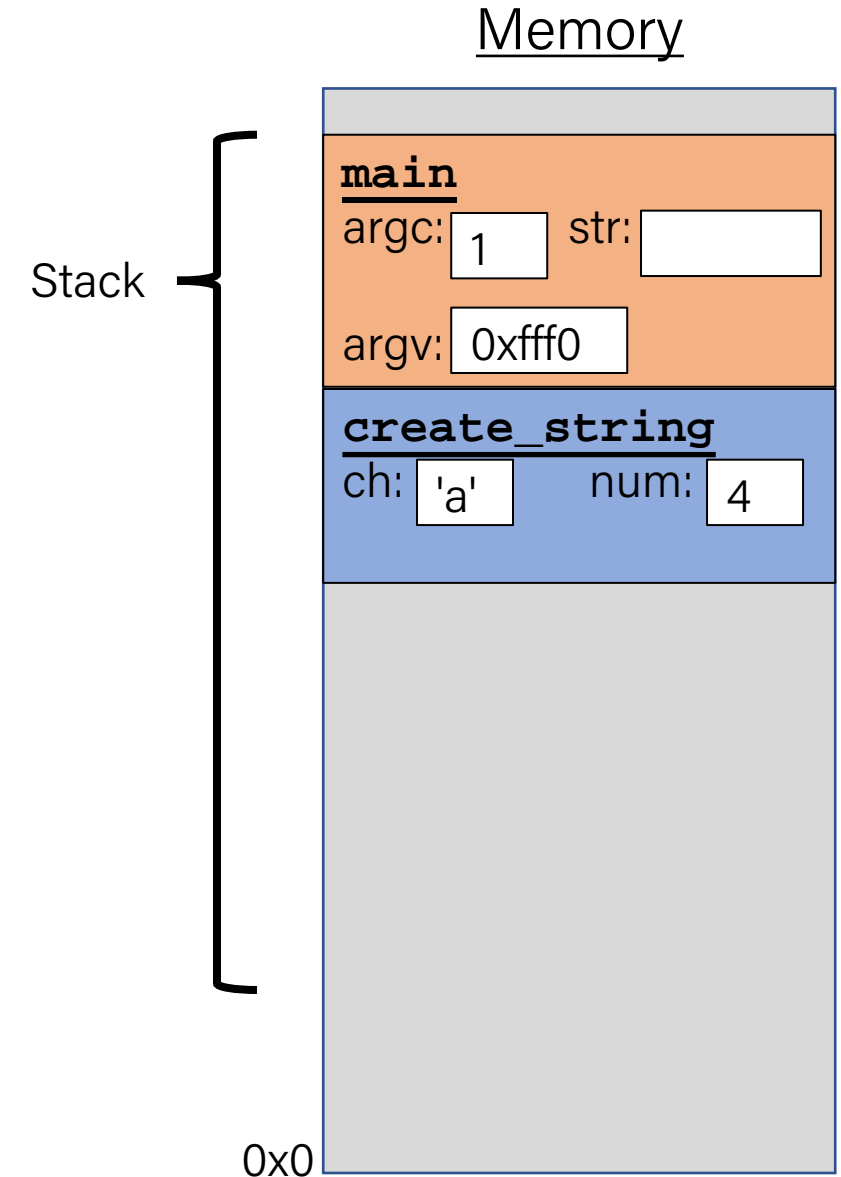
The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



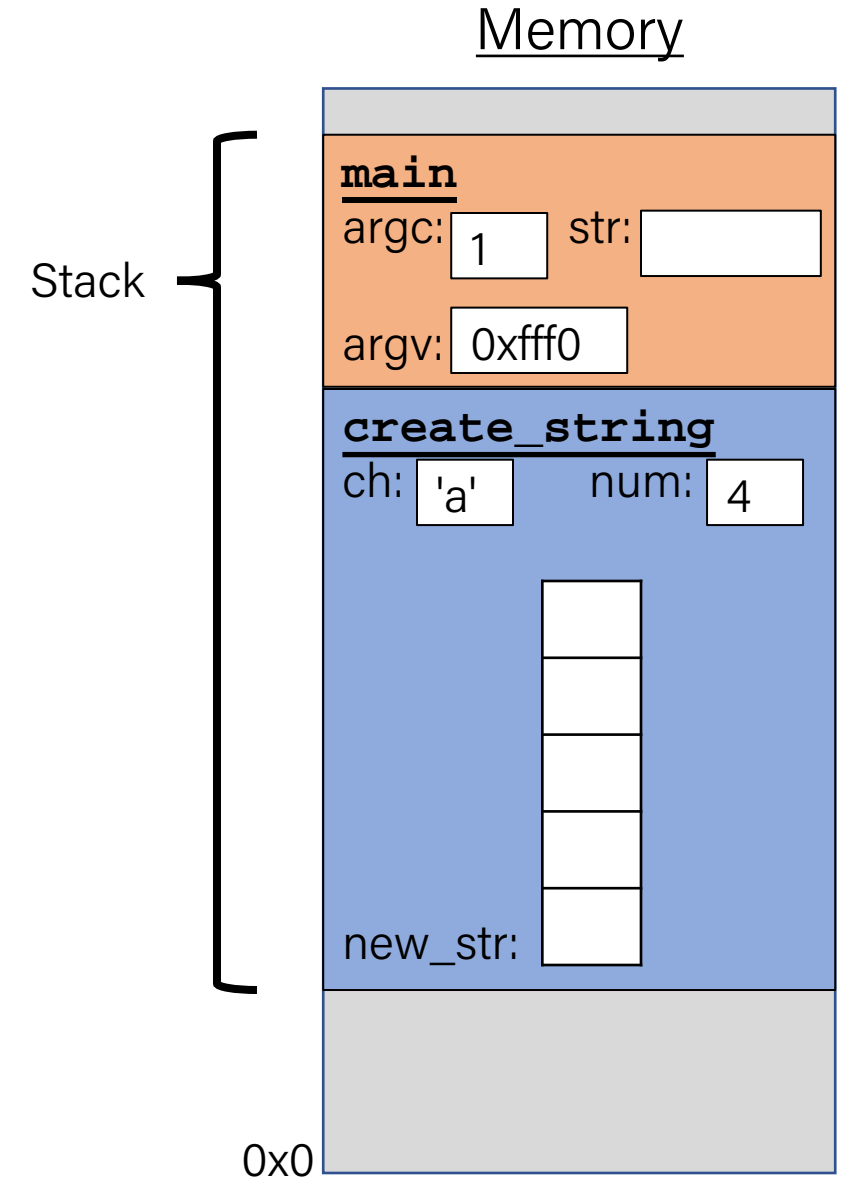
The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Stack

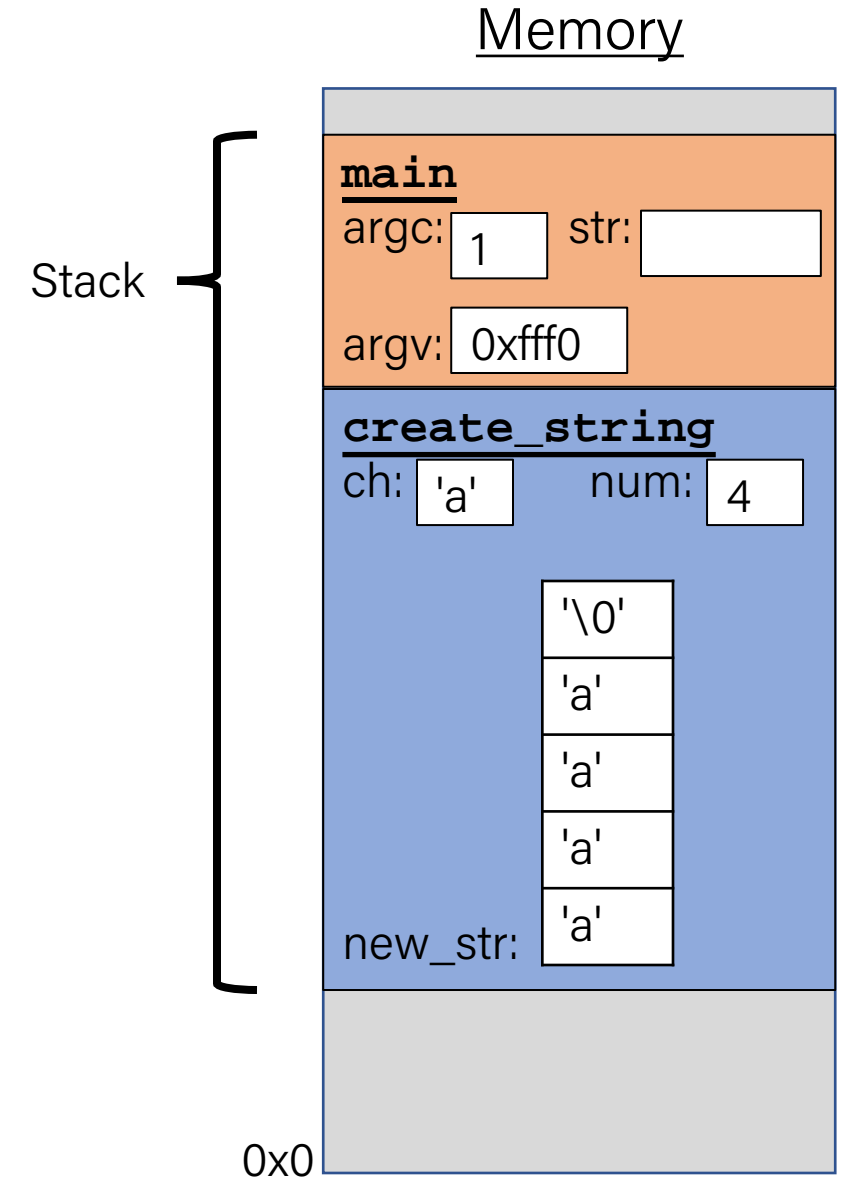
```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```

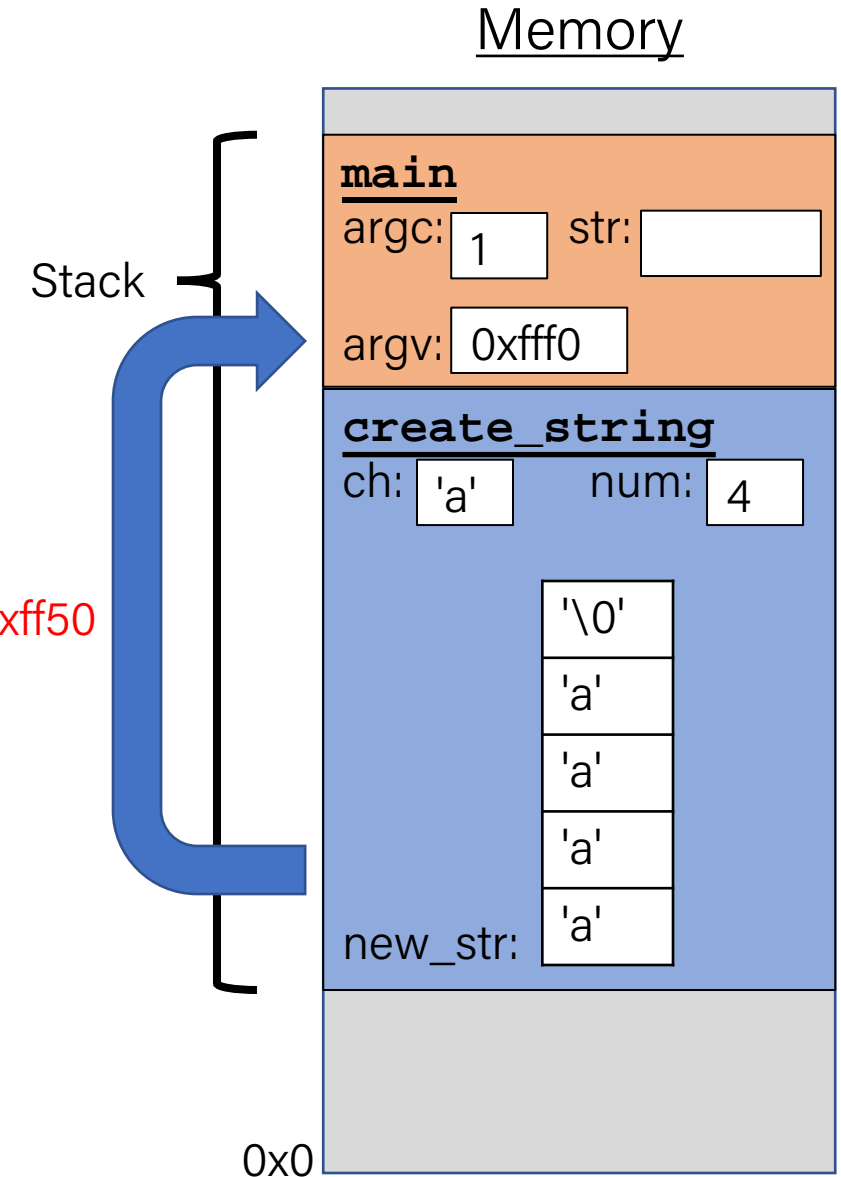


The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```

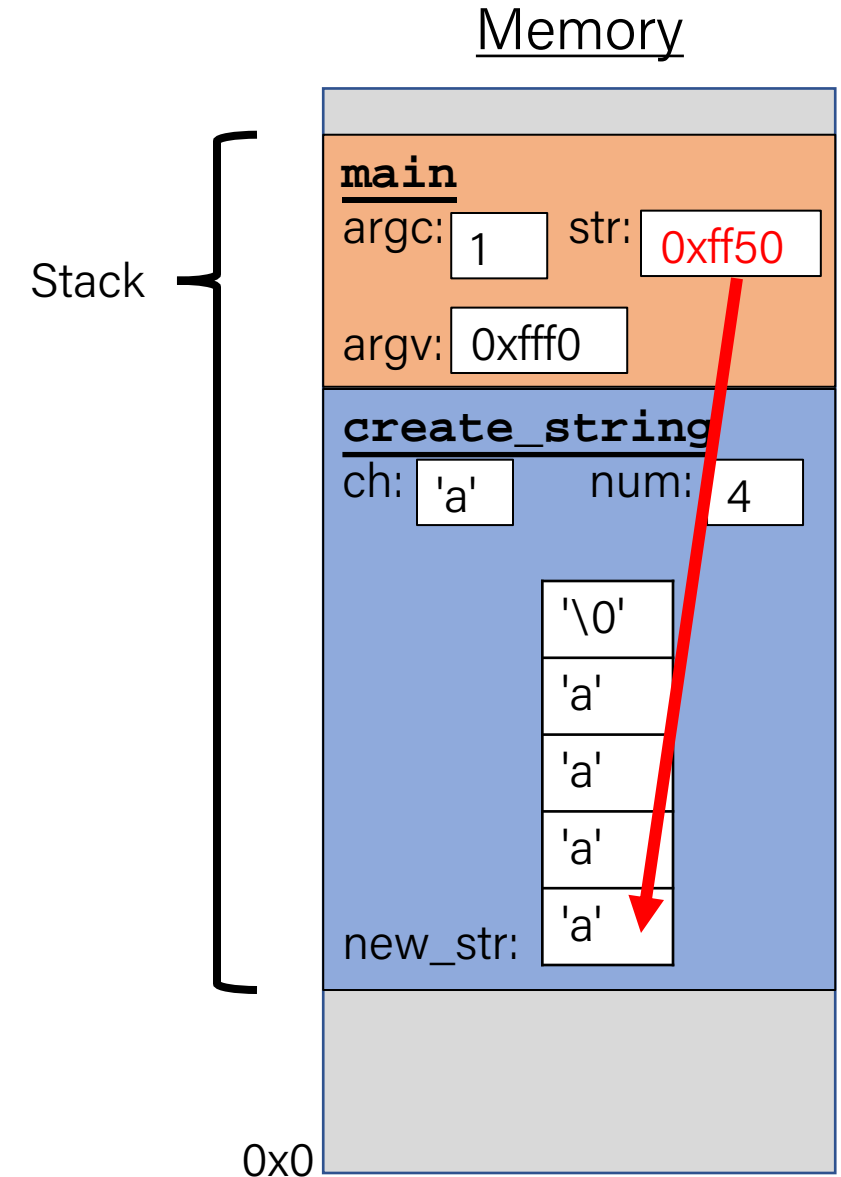
Returns e.g. 0xff50



The Stack

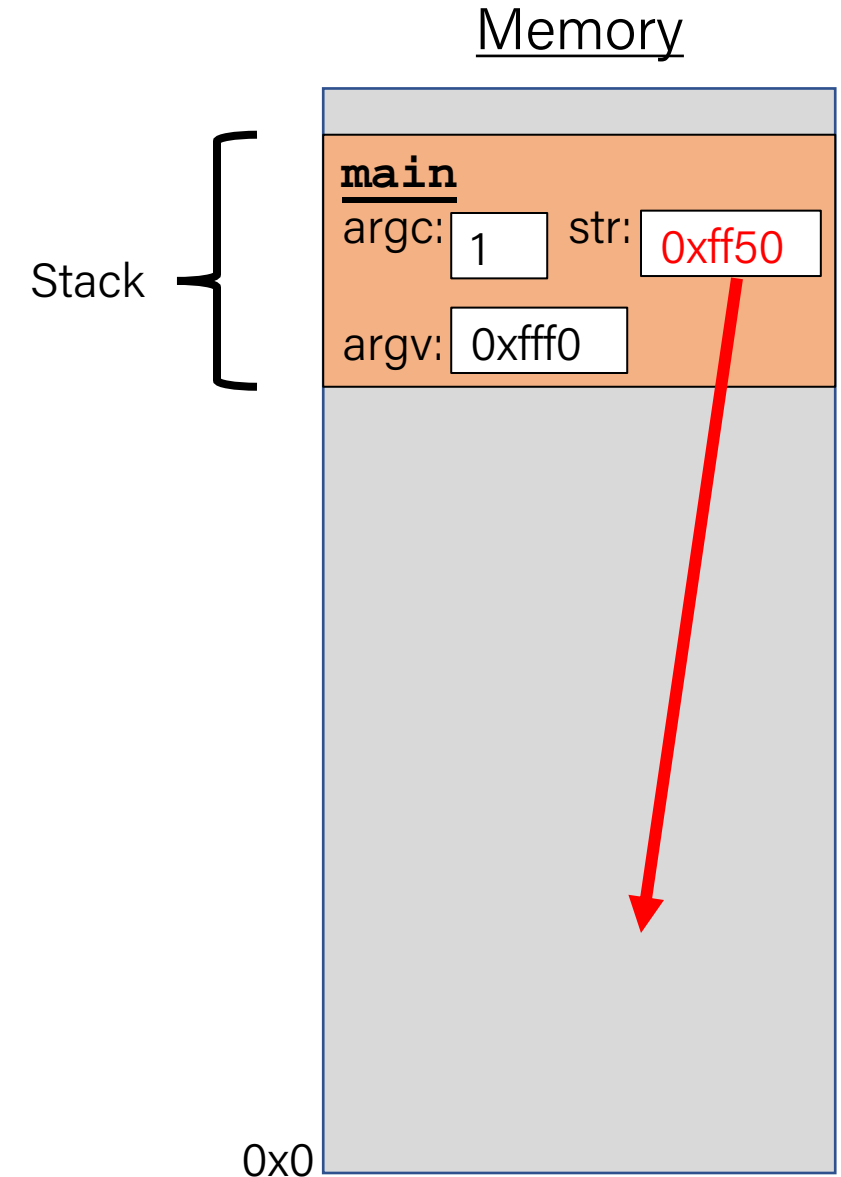
```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```

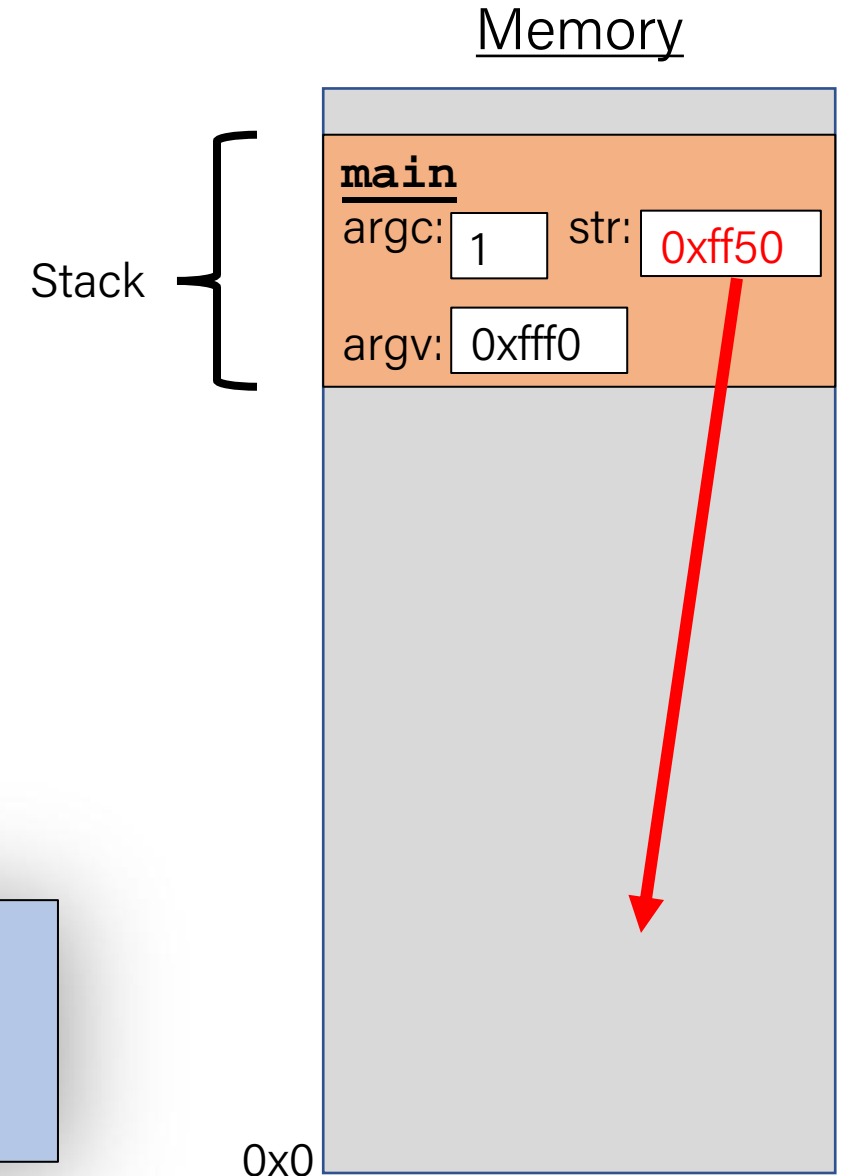


The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

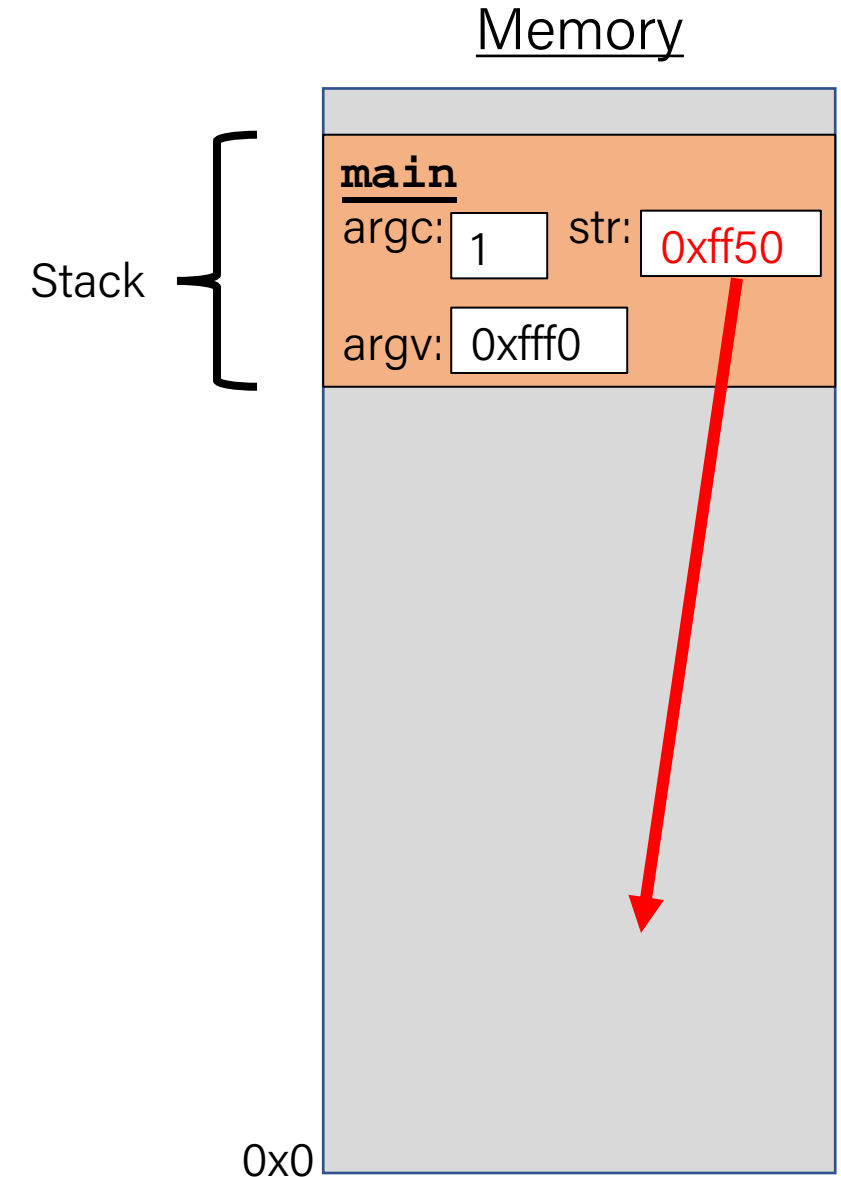
```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```

Problem: local variables go away when a function finishes. These characters will thus no longer exist, and the address will be for unknown memory!



The Stack

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



Stacked Against Us

This is a problem! We need a way to have memory that doesn't get cleaned up when a function exits.

Lecture Plan

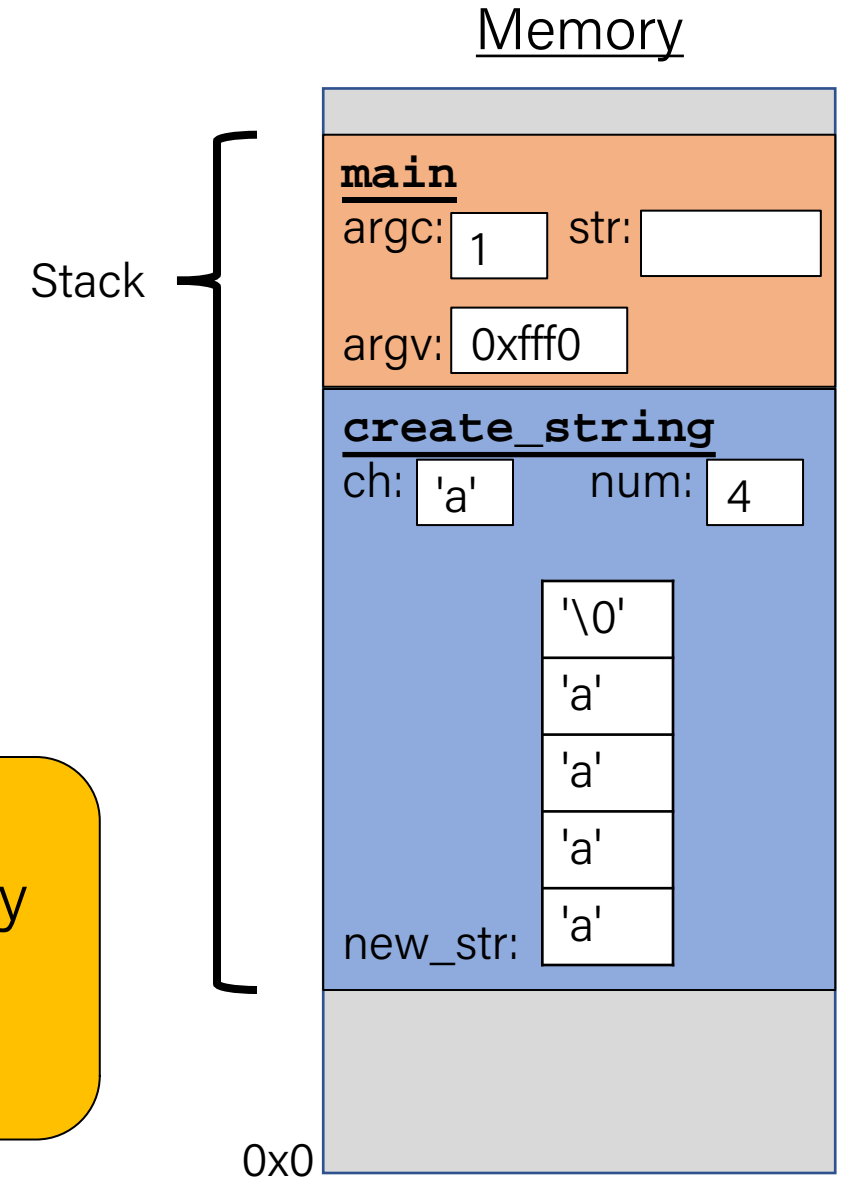
- Arrays in Memory
- Arrays of Pointers
- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

The Heap

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str);  
    return 0;  
}
```

Us: hey C, is there a way to make this variable in memory that isn't automatically cleaned up?

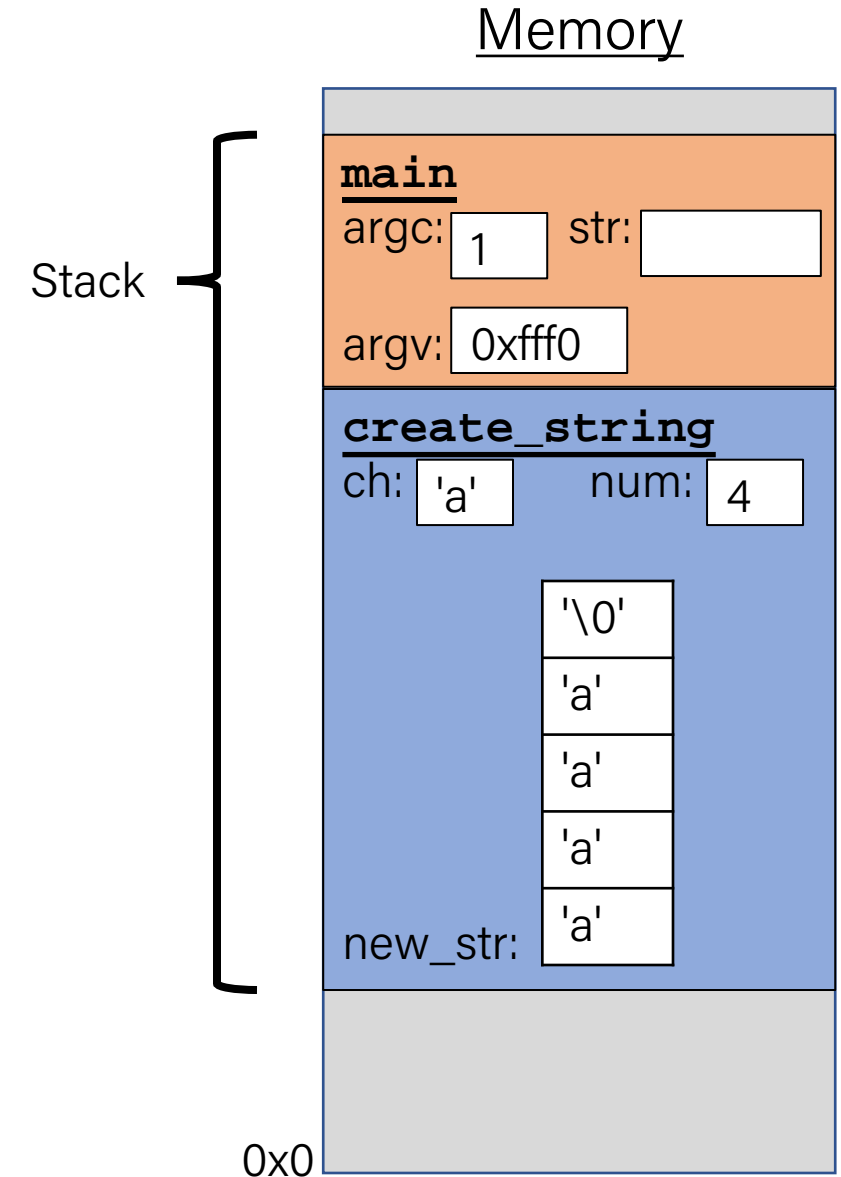


The Heap

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```

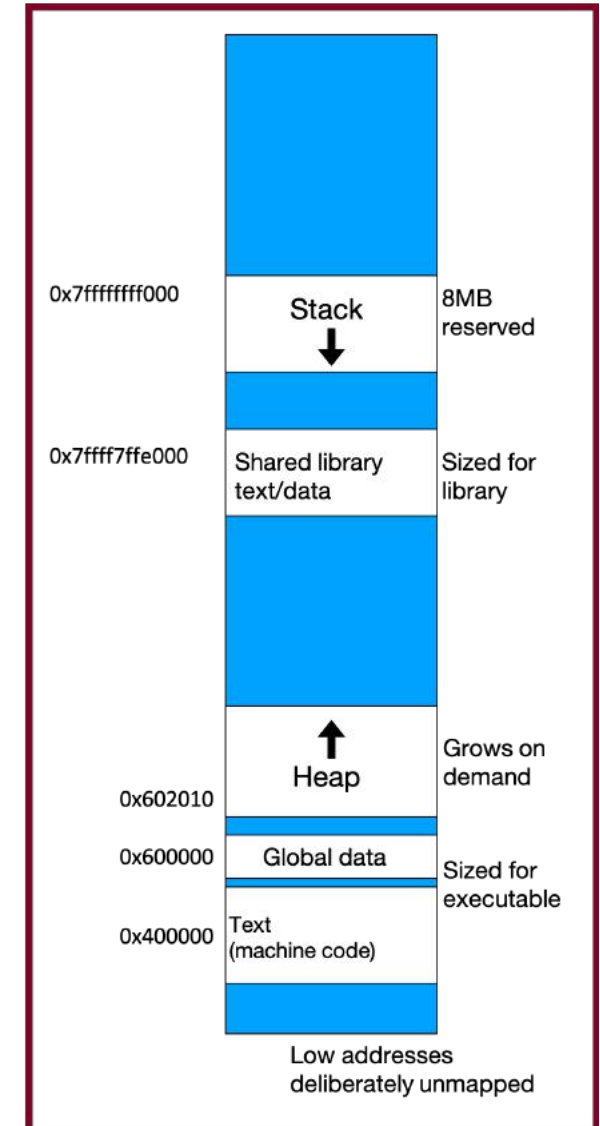
C: sure, but since I don't know when to clean it up anymore, it's your responsibility...



The Heap

- The **heap** is a part of memory that you can manage yourself.
- The **heap** is a part of memory below the stack that you can manage yourself. Unlike the stack, the memory only goes away when you delete it yourself.
- Unlike the stack, the heap grows **upwards** as more memory is allocated.

The heap is **dynamic memory** – memory that can be allocated, resized, and freed during **program runtime**.



malloc

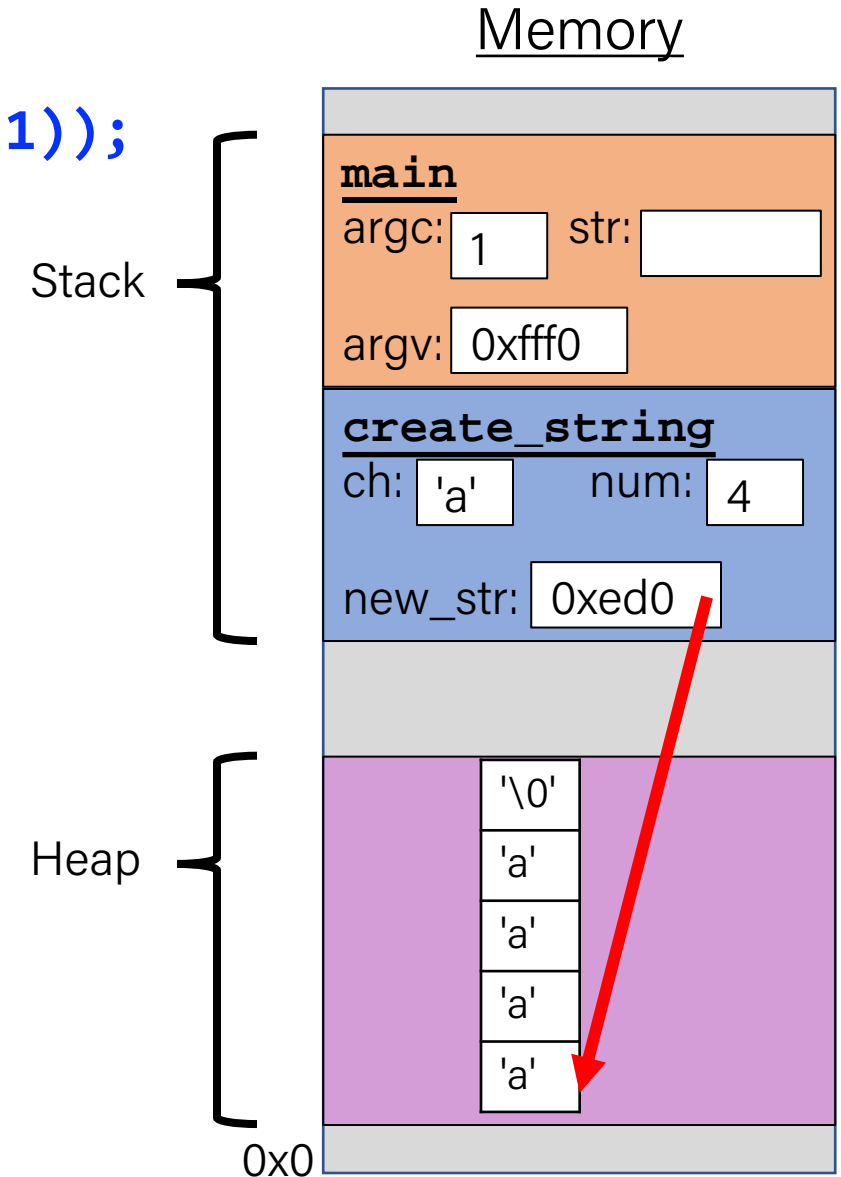
```
void *malloc(size_t size);
```

To allocate memory on the heap, use the **malloc** function ("memory allocate") and specify the number of bytes you'd like.

- This function returns a pointer to *the **starting address** of the new memory*. It doesn't know or care whether it will be used as an array, a single block of memory, etc.
- **void *** means a pointer to generic memory. You can set another pointer equal to it without any casting.
- The memory is *not* cleared out before being allocated to you!
- If **malloc** returns **NULL**, then there wasn't enough memory for this request.

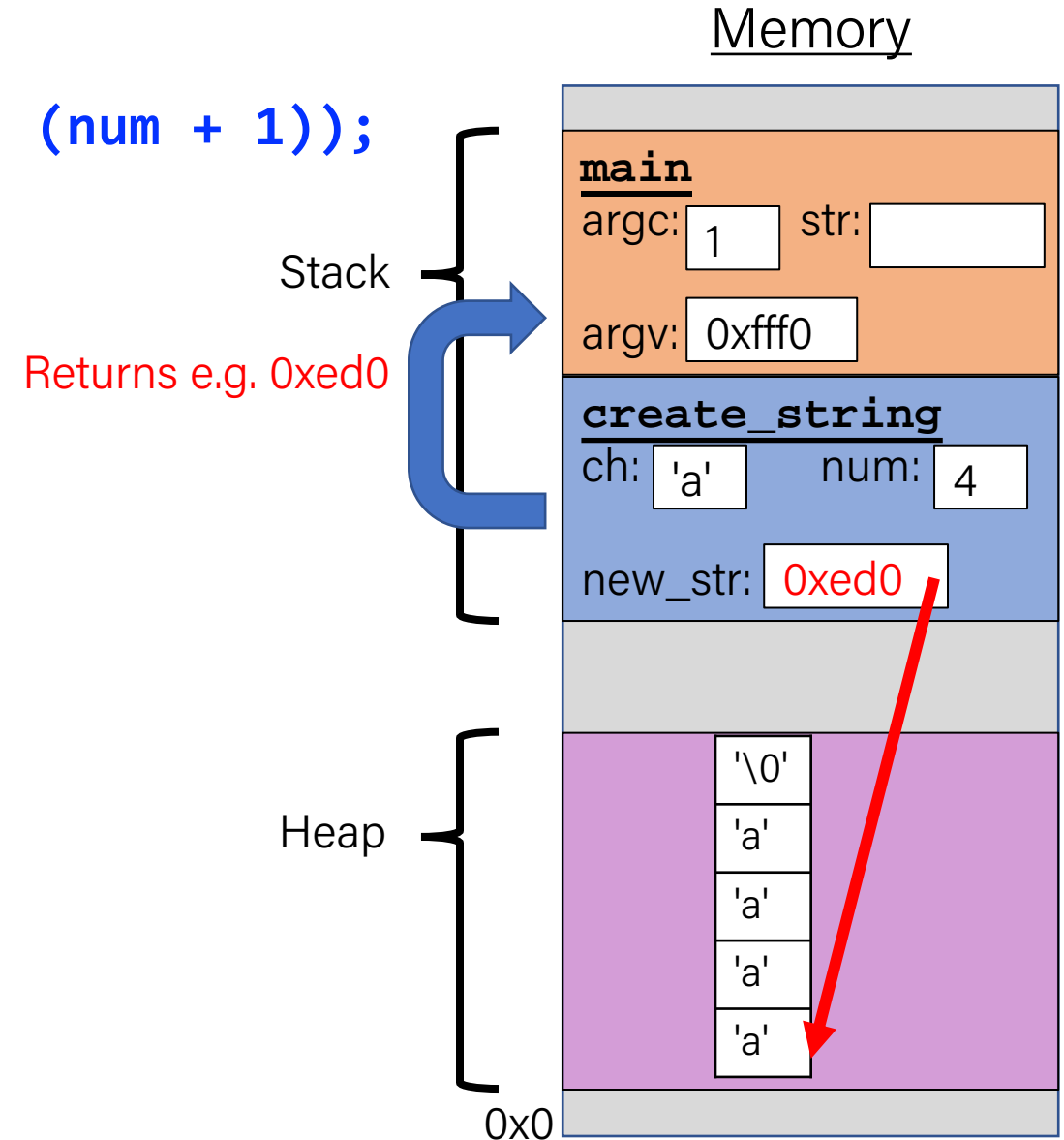
The Heap

```
char *create_string(char ch, int num) {  
    char *new_str = malloc(sizeof(char) * (num + 1));  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Heap

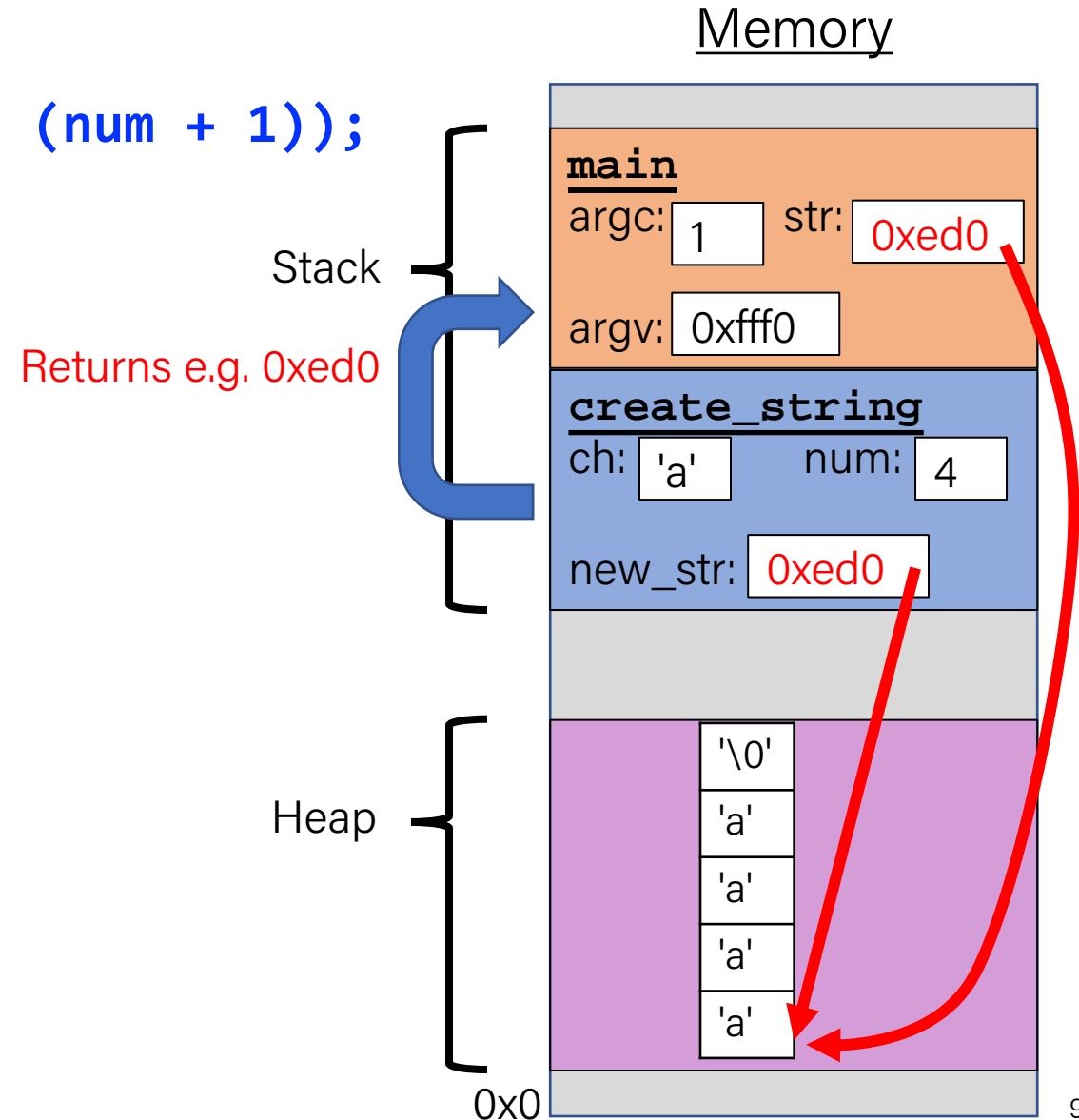
```
char *create_string(char ch, int num) {  
    char *new_str = malloc(sizeof(char) * (num + 1));  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Heap

```
char *create_string(char ch, int num) {  
    char *new_str = malloc(sizeof(char) * (num + 1));  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\\0';  
    return new_str;  
}
```

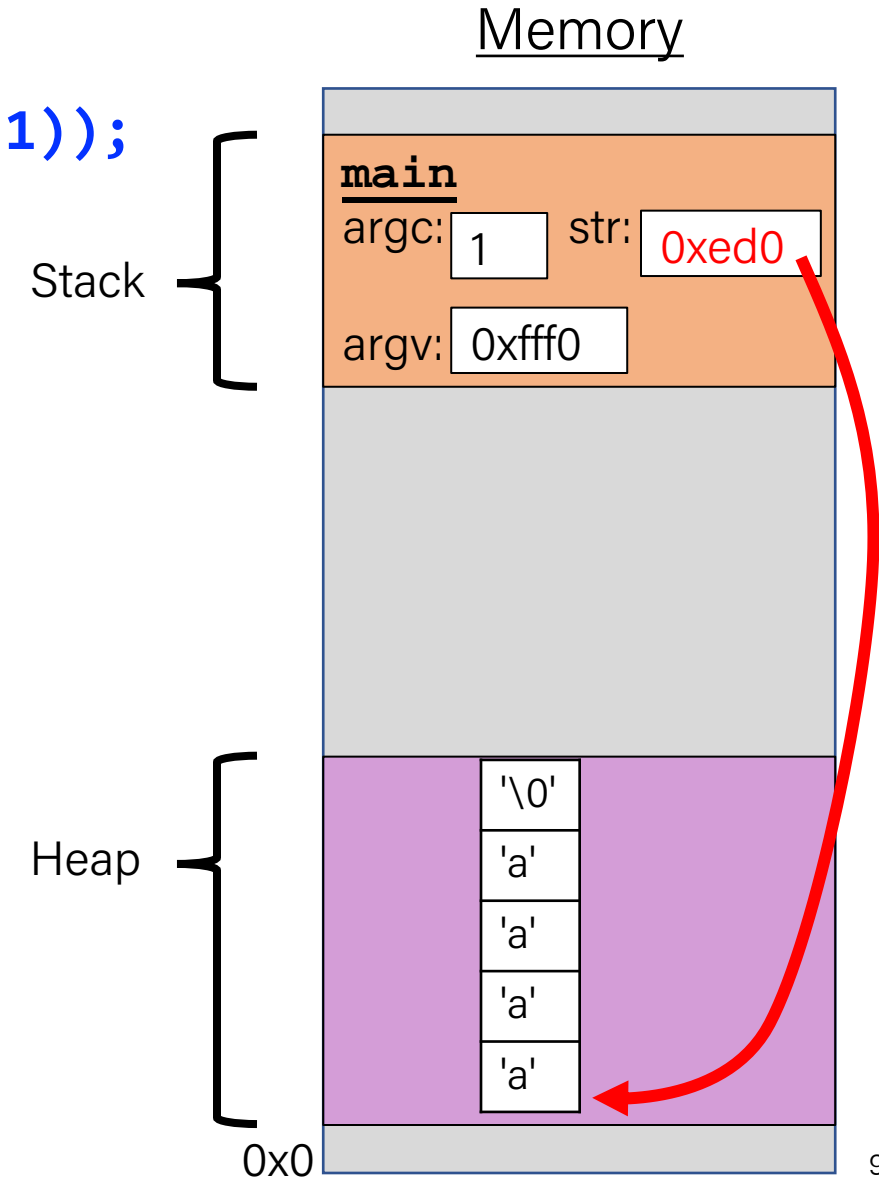
```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Heap

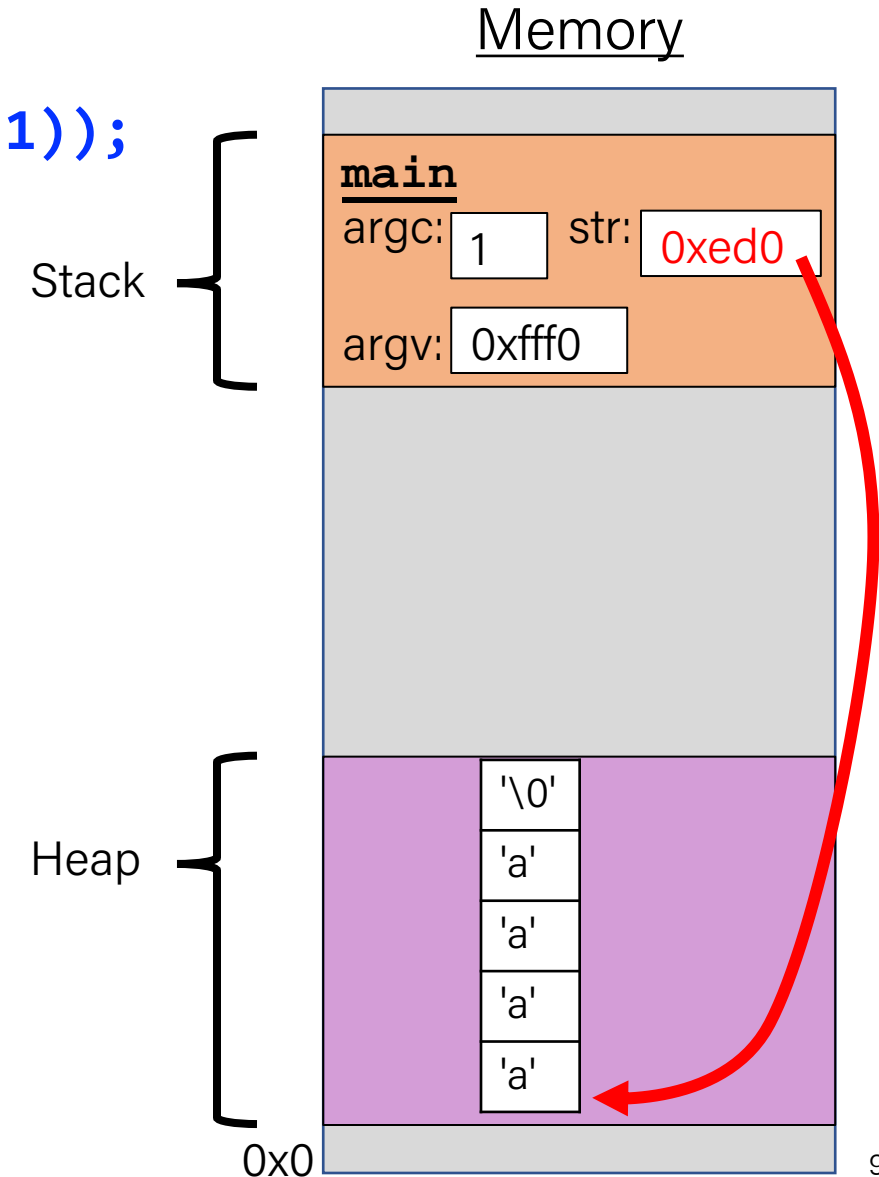
```
char *create_string(char ch, int num) {  
    char *new_str = malloc(sizeof(char) * (num + 1));  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\\0';  
    return new_str;  
}
```

```
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



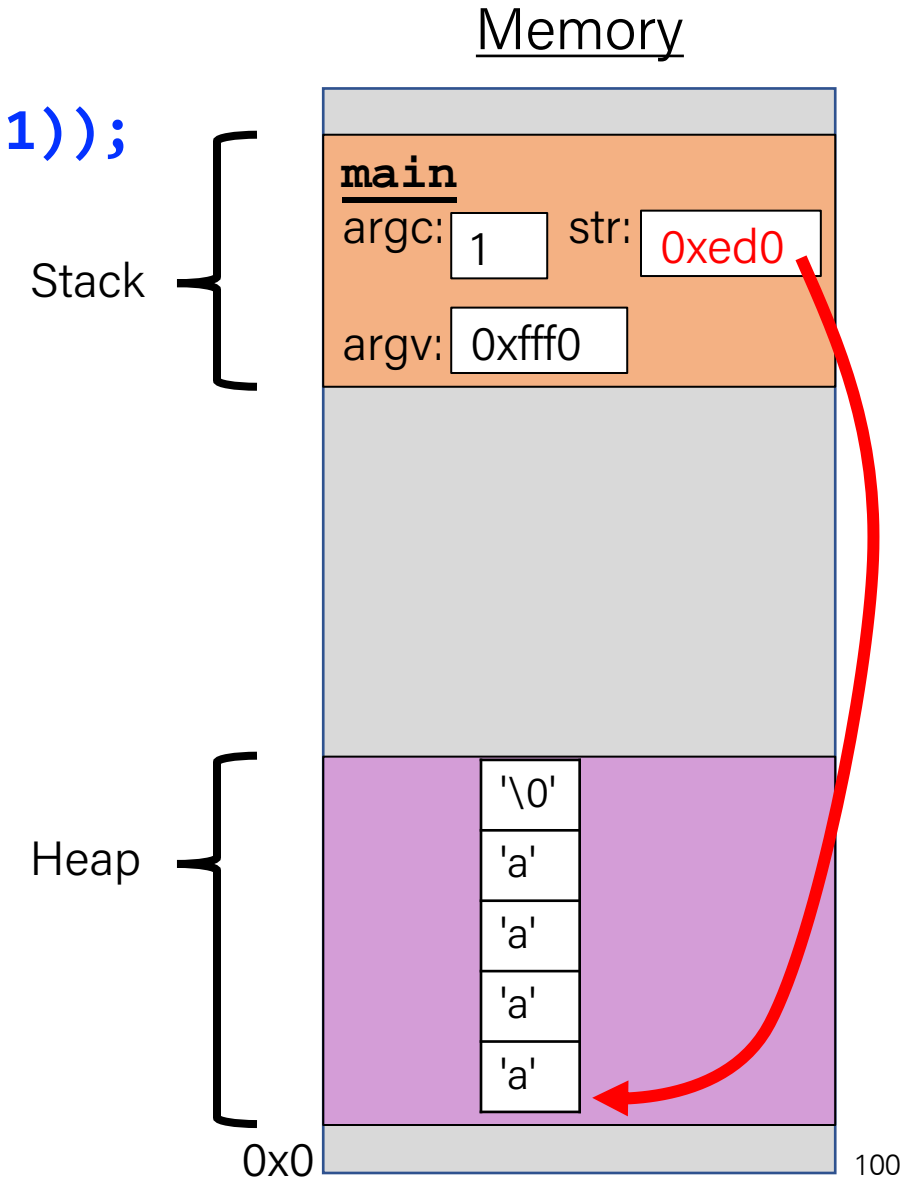
The Heap

```
char *create_string(char ch, int num) {  
    char *new_str = malloc(sizeof(char) * (num + 1));  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



The Heap

```
char *create_string(char ch, int num) {  
    char *new_str = malloc(sizeof(char) * (num + 1));  
    for (int i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
    char *str = create_string('a', 4);  
    printf("%s", str); // want "aaaa"  
    return 0;  
}
```



Exercise: malloc multiples

Let's write a function that returns an array of the first **len** multiples of **mult**.

```
1 int *array_of_multiples(int mult, int len) {  
2     /* TODO: arr declaration here */  
3  
4     for (int i = 0; i < len; i++) {  
5         arr[i] = mult * (i + 1);  
6     }  
7     return arr;  
8 }
```

Line 2: How should we declare arr?

- A. `int arr[len];`
- B. `int arr[] = malloc(sizeof(int));`
- C. `int *arr = malloc(sizeof(int) * len);`
- D. `int *arr = malloc(sizeof(int) * (len + 1));`
- E. Something else



Exercise: malloc multiples

Let's write a function that returns an array of the first **len** multiples of **mult**.

```
1 int *array_of_multiples(int mult, int len) {  
2     /* TODO: arr declaration here */  
3  
4     for (int i = 0; i < len; i++) {  
5         arr[i] = mult * (i + 1);  
6     }  
7     return arr;  
8 }
```

- Use a pointer to store the address returned by malloc.
- Malloc's argument is **the number of bytes** to allocate.


⚠ This code is missing an assertion.

Line 2: How should we declare arr?

- A. `int arr[len];`
- B. `int arr[] = malloc(sizeof(int));`
- ☒ C. `int *arr = malloc(sizeof(int) * len);`
- D. `int *arr = malloc(sizeof(int) * (len + 1));`
- E. Something else

Always assert with the heap

Let's write a function that returns an array of the first `len` multiples of `mult`.



```
1 int *array_of_multiples(int mult, int len) {  
2     int *arr = malloc(sizeof(int) * len);  
3     assert(arr != NULL);  
4     for (int i = 0; i < len; i++) {  
5         arr[i] = mult * (i + 1);  
6     }  
7     return arr;  
8 }
```

- If an allocation error occurs (e.g. out of heap memory!), `malloc` will return `NULL`. This is an important case to check **for robustness**.
- **assert** will crash the program if the provided condition is false. A memory allocation error is significant, and we should terminate the program.

Other heap allocations: calloc

```
void *calloc(size_t nmemb, size_t size);
```

calloc is like **malloc** that **zeros out** the memory for you—thanks, **calloc**!

- You might notice its interface is also a little different—it takes two parameters, which are multiplied to calculate the number of bytes (`nmemb * size`).

```
// allocate and zero 20 ints
```

```
int *scores = calloc(20, sizeof(int));
```

```
// alternate (but slower)
```

```
int *scores = malloc(20 * sizeof(int));
```

```
for (int i = 0; i < 20; i++) scores[i] = 0;
```

- **calloc** is more expensive than **malloc** because it zeros out memory. Use only when necessary!

Other heap allocations: strdup

```
char *strdup(char *s);
```

strdup is a convenience function that returns a **null-terminated**, heap-allocated string with the provided text, instead of you having to **malloc** and copy in the string yourself.

```
char *str = strdup("Hello, world!"); // on heap  
str[0] = 'h';
```

Implementing strdup

How can we implement **strdup** using functions we've already seen?

```
char *myStrdup(char *str) {  
    char *heapStr = malloc(strlen(str) + 1);  
    assert(heapStr != NULL);  
    strcpy(heapStr, str);  
    return heapStr;  
}
```

Cleaning Up with free

```
void free(void *ptr);
```

- If we allocated memory on the heap and no longer need it, it is our responsibility to **delete** it.
- To do this, use the **free** command and pass in the *starting address on the heap for the memory you no longer need*.
- Example:

```
char *bytes = malloc(4);
```

```
...
```



```
free(bytes);
```


free details

Even if you have multiple pointers to the same block of memory, each memory block should only be freed **once**.

```
char *bytes = malloc(4);  
char *ptr = bytes;
```

```
...  
free(bytes);
```

```
...  
free(ptr);
```





✗ Memory at this address was already freed!



You must free the address you received in the previous allocation call; you cannot free just part of a previous allocation.

```
char *bytes = malloc(4);  
char *ptr = malloc(10);
```

```
...  
free(bytes);
```

```
...  
free(ptr + 1);
```

Cleaning Up

You may need to free memory allocated by other functions if that function expects the caller to handle memory cleanup.

```
char *str = strdup("Hello!");
```

```
...
```

```
free(str);    // our responsibility to free!
```

Memory Leaks

- A memory leak is when you allocate memory on the heap, but do not free it.
- Your program should be responsible for cleaning up any memory it allocates but no longer needs.
- If you never free any memory and allocate an extremely large amount, you may run out of memory in the heap!

However, memory leaks rarely (if ever) cause crashes.

- We recommend not to worry about freeing memory until your program is written. Then, go back and free memory as appropriate.
- Valgrind is a very helpful tool for finding memory leaks!

 [More on Valgrind in Lab 3!](#)

free Practice

Freeing Memory

Where should we free memory below so that all memory is freed properly?

```
1  char *str = strdup("Hello");
2  assert(str != NULL);
3  char *ptr = str + 1;
4  for (int i = 0; i < 5; i++) {
5      int *num = malloc(sizeof(int));
6      assert(num != NULL);
7      *num = i;
8      printf("%s %d\n", ptr, *num);
9  }
10 printf("%s\n", str);
```

Freeing Memory

Where should we free memory below so that all memory is freed properly?

```
1  char *str = strdup("Hello");
2  assert(str != NULL);
3  char *ptr = str + 1;
4  for (int i = 0; i < 5; i++) {
5      int *num = malloc(sizeof(int));
6      assert(num != NULL);
7      *num = i;
8      printf("%s %d\n", ptr, *num);
9      free(num);
10 }
11 printf("%s\n", str);
12 free(str);
```

Recap

- Arrays in Memory
- Arrays of Pointers
- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

Next time: *real Loc, Memory bugs*